U. PORTO

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Real-Time Communication Support in IEEE 802.11 Wireless Mesh Networks

Carlos Manuel Dias Viegas

A manuscript submitted to the Doctoral Program in Informatics Engineering (ProDEI) in partial fulfillment of the requirements for the degree of Doctor in Informatics Engineering.

Thesis supervisor: Prof. Francisco Vasques

Thesis co-supervisor: Prof. Paulo Portugal

July, 2015
Porto, Portugal

Faculdade de Engenharia da Universidade do Porto
Departamento de Engenharia Informática
Rua Dr. Roberto Frias, s/n
4200–465 Porto, Portugal

This work was supported by Fundação para a Ciência e a Tecnologia (FCT) through grant SFRH/BD/70077/2010.

POPH PROGRAMA OPERACIONAL POTENCIAL HUMANO
QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
GOVERNO DA REPÚBLICA PORTUGUESA
UNIÃO EUROPEIA Fundo Social Europeu

To my family, for all unconditional support and affection.

Acknowledgments

It is hard to express our feelings and gratitude in words, and it is even harder in a foreign language. So, I shall write my acknowledgments in portuguese.

A conclusão deste trabalho representa um momento muito especial para mim, entretanto o seu término não teria sido possível sem a colaboração de algumas pessoas, às quais gostaria de expressar os meus agradecimentos:

Ao Francisco Vasques, professor da Universidade do Porto, pelo exercício exemplar da sua função de orientador, mostrando-se sempre disponível e interessado em responder às questões, dúvidas e problemas que surgiram durante esta tese. A ti Francisco, sou grato pela oportunidade que me deste em poder integrar o teu grupo de pesquisa e realizar este trabalho. Agradeço por toda a confiança em mim depositada.

Ao Paulo Portugal, professor da Universidade do Porto, por todo o apoio e disponibilidade em coorientar este trabalho. As discussões científicas que tivemos e os resultados obtidos foram fundamentais para este trabalho.

Aos meus pais, Carlos e Marina, pelo total e incondicional apoio na realização deste projeto, bem como em outras etapas da minha vida. Sou grato para toda a vida pela dedicação e esforço que vocês sempre fizeram para dar-me uma educação de qualidade. Hoje, a concretização deste trabalho é o reconhecimento de que tudo valeu a pena. Obrigado por tudo!

À minha esposa Cíntia Camila, amada e fiel companheira, por todo o apoio e incentivo para a realização deste projeto. Agradeço-te por teres embarcado nesta aventura de vir para Portugal, deixando a família e abrindo mão dos teus projetos pessoais para ficar comigo. Sou eternamente grato a ti por isso e por muito mais.

Ao meu irmão Mário Carlos, pelo incentivo e pelas longas discussões filosóficas sobre a vida, que foram fundamentais para a formação do meu caráter. Este trabalho não teria sido possível sem os teus ensinamentos, os quais ficarão para toda a vida: “Praticar, repetir, insistir!”

À minha irmã Iasmin Preciosa, pelo carinho e amizade, bem como pelas divertidas brincadeiras que sempre ajudaram a descontrair o momento.

À minha sogra Nazaré, pelos sempre importantes conselhos e ensinamentos a respeito da vida acadêmica, os quais foram muito úteis para este trabalho e também serão para a minha vida acadêmico-profissional.

À minha tia Teresa e minha avó Leonor, por todo o apoio durante a realização deste trabalho. Obrigado por toda a dedicação e preocupação comigo durante todos estes anos.

Ao Luiz Affonso Guedes, professor da Universidade Federal do Rio Grande do Norte, pelo incentivo e por recomendar-me ao professor Francisco Vasques para integrar o seu grupo de pesquisa e poder desenvolver este projeto de investigação.

Ao Ricardo Moraes, professor da Universidade Federal de Santa Catarina, pela troca de conhecimentos e pela oportunidade de trabalharmos juntos na realização de parte deste trabalho. Os teus conselhos sempre foram muito pertinentes e úteis para aprimorar a qualidade deste trabalho.

Ao Ivanovitch Silva, pela amizade e apoio durante todo o doutoramento. Sou grato a você pelas dicas e sugestões, bem como por incentivar-me a realizar os concursos em busca de seguir a carreira acadêmica. Como você bem dizia: "A vida é dinâmica!"

Ao Daniel Costa, pela amizade, bem como pelo apoio e incentivo na fase final da defesa do doutoramento.

Ao Silvio Sampaio, pelas discussões científicas e troca de conhecimentos e experiências, importantes para a realização de parte deste trabalho.

Aos amigos Ondina e Madureira, pelo acolhimento e disponibilidade em ajudarem-me a estabelecer moradia na cidade do Porto. Sou grato pela vossa confiança.

Aos demais amigos que, direta ou indiretamente, colaboraram com este trabalho e que também ajudaram a tornar o convívio mais alegre e descontraído: Rodrigo Lange, Pedro Rocha, Odilson Vale, Claudia Castro, Rui Chilro, Tiago Fernandes, Erico Leão, Prof. Carlos Montez, Prof. Romulo Oliveira, Robson Costa, Leonardo Rodrigues, Benedito Bittencourt, Renata Oliveira, Danilo Jodas, Mara Martins e Prof. Avelino Dias. O meu muito obrigado a todos vocês.

Por fim, agradeço à Fundação para a Ciência e a Tecnologia (FCT), ao Departamento de Engenharia Mecânica e Gestão Industrial (DEMEGI) e à Unidade de Integração de Sistemas e Processos Automatizados (UISPA) do Instituto de Engenharia Mecânica (IdMEC – pólo FEUP) pelo apoio financeiro e logístico neste estudo.

Carlos Manuel Dias Viegas
July, 2015

Abstract

Real-Time Communication Support in IEEE 802.11 Wireless Mesh Networks

Author
Carlos Manuel Dias Viegas

Thesis supervisor
Prof. Francisco Vasques

Thesis co-supervisor
Prof. Paulo Portugal

The IEEE 802.11s standard has been proposed to specify a wireless mesh infrastructure over traditional IEEE 802.11 wireless local area networks (WLANs), enabling the support of wireless services for a wide range of applications through a multi-hop wireless relaying infrastructure. With the increased popularity of wireless mesh networks (WMNs), there is a current trend to deploy 802.11s-based WMNs in industrial environments, where real-time (RT) control applications may benefit from increased communication performance. However, the medium access control (MAC) mechanisms of 802.11s WMN standard present some relevant impairments for quality of service (QoS) provisioning in multi-hop communication scenarios, namely when the wireless channel is shared with uncontrolled non-RT traffic sources. Therefore, one of the fundamental questions that must be addressed when setting-up WMNs in industrial environments is: "How to guarantee the QoS requirements for RT data when the wireless channel is shared with uncontrolled non-RT traffic sources?"

Within this context, the main objective of this thesis is to provide means to mitigate the MAC impairments on QoS provisioning, and, therefore, to support real-time communication in 802.11s WMNs. Accordingly, this thesis presents a study of the state-of-the-art in the context of RT communication support, pointing out the most relevant challenges and impairments for QoS provisioning in 802.11-based WMNs, as well as some of the proposed QoS solutions in the literature.

Beyond this study, an extensive simulation assessment of the default MAC mechanism of 802.11s WMN standard has been done, that demonstrates its inability to support RT communication when the wireless channel is shared with uncontrolled non-RT traffic sources. The assessment results indicate that RT traffic is severely impacted by the presence of non-RT traffic, suggesting that the MAC mechanism should be aided by resource reservation mechanisms to fulfill the QoS requirements for RT traffic in WMNs.

For the simulation assessments performed within this thesis, the following assumptions have been made: (i) the real-time communication environment is established with a stationary

topology limited by boundary wireless mesh stations; (ii) the wireless medium is shared among RT and non-RT traffic sources, in a fully-distributed channel access control; (iii) the network utilization imposed by the interfering stations (i.e. stations transmitting non-RT traffic) is out of the sphere-of-control of the MAC protocol.

In this sense, this thesis proposes a new resource reservation (RR) scheme to aid the default MAC mechanism of 802.11s, to support RT communication in WMNs when the wireless channel is shared with non-RT traffic sources. The proposed scheme, called mesh resource reservation (MRR) scheme, reserves time intervals throughout an RT path, during which the neighboring non-RT traffic sources are compelled to contend for the channel in a slowdown contention mode. The objective of this slowdown contention mode is to alleviate the surrounding interferences over the real-time communication. The effectiveness of the MRR scheme has been assessed by a set of simulation experiments, and compared with other RR schemes available in the literature. The results have demonstrated that, in general, RR schemes are able to mitigate the most relevant impairments regarding the RT communication support in WMNs. Besides, the MRR scheme is also able to efficiently control the impact from interfering non-RT traffic sources in the mesh network.

Keywords: Real-time communication; Quality of service; Resource reservation; IEEE 802.11s; Wireless mesh networks.

Resumo

Real-Time Communication Support in IEEE 802.11 Wireless Mesh Networks

Autor
Carlos Manuel Dias Viegas

Orientador da tese
Prof. Francisco Vasques

Coorientador da tese
Prof. Paulo Portugal

O padrão IEEE 802.11s foi proposto para especificar uma infraestrutura emalhada sem fios sobre as tradicionais redes de área local baseadas no padrão sem fios IEEE 802.11, desta forma ampliando o provimento de serviços sem fios para as aplicações através de uma infraestrutura de encaminhamento de múltiplos saltos. Com a crescente popularidade das redes emalhadas sem fios, atualmente existe uma tendência para a implantação de redes emalhadas baseadas no padrão 802.11s em ambientes industriais, nos quais as aplicações de controlo de tempo-real podem beneficiar-se de um desempenho melhorado. Entretanto, os mecanismos de controlo de acesso ao meio do padrão 802.11s apresentam falhas relevantes no que respeita ao provisionamento de qualidade de serviço em cenários de comunicação em múltiplos saltos, nomeadamente quando o canal sem fio é compartilhado com fontes não-controladas de tráfego não-tempo-real. Desta forma, uma das questões fundamentais que deve ser abordada quando as redes emalhadas sem fios são implantadas em ambientes industriais é: "Como garantir os requisitos de qualidade de serviço do tráfego de tempo-real quando o canal sem fio é compartilhado com fontes não-controladas de tráfego não-tempo-real?"

Neste contexto, o principal objetivo desta tese é de fornecer meios para minimizar as falhas dos mecanismos de controlo de acesso ao meio no que respeita ao provisionamento de qualidade de serviço, e, assim, dar suporte à comunicação de tempo-real em redes emalhadas sem fios baseadas no padrão 802.11s. Por conseguinte, esta tese apresenta um estudo do estado da arte no contexto do suporte à comunicação de tempo-real, destacando os desafios e as falhas mais relevantes para o provisionamento de qualidade de serviço em redes emalhadas 802.11s, assim como também apresenta algumas das soluções de qualidade de serviço propostas na literatura.

Além deste estudo, foi realizada uma extensiva avaliação por simulações do mecanismo de controlo de acesso ao meio, por defeito, do padrão 802.11s, onde é demonstrada a sua incapacidade em prover suporte à comunicação de tempo-real quando o canal sem fio é compartilhado com fontes não-controladas de tráfego não-tempo-real. Os resultados da avaliação indicam que o tráfego de tempo-real sofre um elevado impacto causado pela presença de tráfego não-tempo-real, sugerindo que o mecanismo de controlo de acesso ao meio deve ser auxiliado por mecanismos de reserva de recursos para cumprir os requisitos de qualidade de serviço do tráfego de tempo-real nas redes emalhadas sem fios.

Para as avaliações por simulação realizadas nesta tese, foram considerados os seguintes pressupostos: (i) o ambiente de comunicação de tempo-real é estabelecido através de uma topologia estacionária, limitada por estações de malha sem fios na fronteira; (ii) o canal sem fio é compartilhado entre fontes de tráfego de tempo-real e de não-tempo-real, com um controlo do canal totalmente distribuído; (iii) a utilização da rede imposta pelas estações de interferência (ou seja, que transmitem tráfego não-tempo-real) está fora do domínio do protocolo de controlo de acesso ao meio.

Neste sentido, esta tese propõe um novo esquema de reserva de recursos para auxiliar o mecanismo de controlo de acesso ao meio, por defeito, do padrão 802.11s, a dar suporte à comunicação de tempo-real em redes emalhadas sem fios, especialmente quando o canal sem fio é compartilhado com fontes de tráfego não-tempo-real. O esquema proposto, denominado Mesh Resource Reservation (MRR), reserva intervalos de tempo ao longo de todo um caminho de comunicação de tempo-real, durante os quais as fontes de tráfego não-tempo-real na vizinhança são obrigadas a competir pelo acesso ao canal em modo de abrandamento. O objetivo deste modo é de diminuir as interferências circundantes sobre a comunicação de tempo-real. A eficácia do esquema MRR foi avaliada através de um conjunto de experimentos de simulação, e comparado com outros esquemas de reserva de recursos disponíveis na literatura. Os resultados demonstraram que, em geral, os esquemas de reserva de recursos são capazes de mitigar as falhas mais relevantes relacionadas ao suporte da comunicação de tempo-real em redes emalhadas sem fios. Além disso, o esquema MRR é também capaz de controlar de forma eficiente o impacto das interferências causadas pelas fontes de tráfego não-tempo-real na rede.

Palavras-chave: Comunicação de tempo-real; Qualidade de serviço; Reserva de recursos; IEEE 802.11s; Redes emalhadas sem fios.

Contents

List of figures

List of tables

List of acronyms

AARF	Adaptive ARF
AC	Access category
AC-ANBR	Admission control based on active neighbor bandwidth reservation
ACK	Acknowledgment
AIFS	Arbitration interframe space
AIFSN	AIFS number
AODV	Ad hoc on-demand distance vector
AODV-MRCR	AODV-multi radio with channel reservation
AP	Access point
ARF	Automatic rate fallback
BE	Best effort
BEB	Binary exponential backoff
BK	Background
BO	Backoff timer
BOR/AC	Bandwidth-aware opportunistic routing protocol with admission control
BPSK	Binary phase-shift keying
BSS	Basic service set
CAFMA	Channel assignment and fast MAC architecture
CAP	Controlled access phase
CCK	Complementary code keying
CDF	Cumulative distribution function
CF-Poll	Contention-free-poll
CFP	Contention free period
CL	Controlled load
CP	Contention period
CSMA/CA	Carrier sense multiple access with collision avoidance
CTR	Clear to reserve
CTS	Clear to send
CW	Contention window
DA	Destination address
DARE	Distributed end-to-end allocation of time slots for real-time
DBPS	Data bits per symbol
DCF	Distributed coordination function
DiffServ	Differentiated services
DIFS	DCF interframe space
DMT	Deadline miss threshold
DRAV	Directional RAV
DS	Distribution system
DSSS	Direct sequence spread spectrum

DTIM	Delivery traffic indication message
EDCA	Enhanced distributed channel access
EDCA/RR	EDCA with resource reservation
EDCAF	EDCA function
EDF	Earliest deadline first
EE	Excellent effort
eMCCA	Enhanced MCCA
EMDA	Enhanced mesh deterministic access
ERP	Extended rate PHY
ESS	Extended service set
FAR	Fair access rate
FARF	Fast rate reduction ARF
FCS	Frame check sequence
FFMAC	Fast forward medium access control
FHSS	Frequency hoping spread spectrum
GANN	Gate announcement
GFSK	Gaussian phase-shift keying
HC	Hybrid coordinator
HCCA	HCF controlled access
HCF	Hybrid coordination function
HMCP	Hybrid multi-channel protocol
HR/DSSS	High rate direct sequence spread spectrum
HT	High throughput
HTTP	Hypertext transfer protocol
HWMP	Hybrid wireless mesh protocol
ID	Identification
IE	Information element
IEEE	Institute of electrical and electronics engineers
IETF	Internet engineering task force
IntServ	Integrated services
IP	Internet protocol
IR	Interference
ISM	Industrial scientific and medical
JRCAP	Joint routing and channel assignment protocol
LAN	Local area network
MAC	Medium access control
MADV	MCCAOP advertisement
MAF	MCCA access fraction
MARE	Medium access through reservation
MBRWMN	Multi-hop bandwidth reservation in WMN
MBSS	Mesh basic service set
MCCA	MCF controlled channel access
MCCAOP	MCCA opportunity
MCF	Mesh coordination function
MDA	Mesh deterministic access
MesTiC	Mesh-based traffic and interference-aware channel-assignment

MIFS	Mesh interframe space
MIMO	Multiple-input/multiple-output
MMAC	Multi-channel MAC
MPM	Mesh peering management
MREP	MRR reservation reply
MREQ	MRR reservation request
MRR	Mesh resource reservation
MSDU	MAC service data unit
MTOP	Multi-hop transmission opportunity
MU-MIMO	Multi-user multiple-input/multiple-output
NAV	Network allocation vector
NC	Network control
NIC	Network interface controller
NIST	National institute of standards and technology
ns-3	Network simulator 3
OFDM	Orthogonal frequency-division multiplexing
PC	Point coordinator
PCF	Point coordination function
PERR	Path error
PHY	Physical
PIFS	PCF interframe space
PLCP	PHY layer convergence procedure
PRE	PLCP preamble
PREP	Path reply
PREQ	Path request
QAM	Quadrature amplitude modulation
QMF	QoS management frame
QoS	Quality of service
QPSK	Quadrature phase-shift keying
R-HWMP	Reservation-based HWMP
RA	Receiver address
RANN	Root announcement
RAV	Resource allocation vector
RBAR	Receiver-based auto rate
RF	Radio frequency
RR	Resource reservation
RREP	Route reply
RREQ	Route request
RSVP	Resource reservation protocol
RT	Real-time
RTR	Request to reserve
RTS	Request to send
Rx	Receiver
s/r	Sender/receiver
SA	Source address
SARF	Static retransmission rate ARF

SIFS	Short interframe space
SIG	Signal
SIGEX	Signal extension
SISO	Single-input/single-output
SN	Sequence number
SNR	Signal-to-noise ratio
STA	Station
SU-MIMO	Single-user multiple-input/multiple-output
SYM	Symbol
TA	Transmitter address
TCP	Transmission control protocol
TMAC	Timestamp-ordered MAC
TSPEC	Traffic specification
TTL	Time to live
Tx	Transmitter
TXOP	Transmission opportunity
UDP	User datagram protocol
UP	User priority
VHT	Very high throughput
VI	Video
VO	Voice
VoIP	Voice over IP
WAM	Weighted airtime metric
WLAN	Wireless local area network
WMN	Wireless mesh network

List of publications

Five research papers have been published within the context of this thesis, being one journal paper, one book chapter and three conference papers. In addition, currently, there is an additional journal paper submitted to a peer-review journal, which is yet in the reviewing process.

Journal papers

1. C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources. *EURASIP Journal on Wireless Communications and Networking*, 2014(219):1–15, 2014. `http://dx.doi.org/10.1186/1687-1499-2014-219`

2. C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. A multi-hop resource reservation scheme to support real-time communication in IEEE 802.11s wireless mesh networks. SUBMITTED FOR PUBLICATION IN *Ad Hoc Networks*, Elsevier, 2015.

Book chapters

1. C. M. D. Viegas, F. Vasques, P. Portugal. Real-Time Communication Support in IEEE 802.11-based Wireless Mesh Networks. In M. Khosrow-Pour (Ed.), *Encyclopedia of Information Science and Technology*, ch. 713, pp. 7247–7259. IGI Global, Hershey, PA, USA, 3rd ed., 2014. `http://dx.doi.org/10.4018/978-1-4666-5888-2.ch713`

Conference papers

1. C. M. D. Viegas, F. Vasques, P. Portugal. Evaluating the impact of uncontrolled traffic sources upon real-time communication in IEEE 802.11s mesh networks. In *12th IEEE International Conference on Industrial Informatics (INDIN'2014)*, pp. 106–111, Porto Alegre, RS, Brazil, July 2014. `http://dx.doi.org/10.1109/INDIN.2014.6945492`

2. C. M. D. Viegas, S. Sampaio, F. Vasques, P. Portugal, P. Souto. Assessment of the Interference Caused by Uncontrolled Traffic Sources upon Real-Time Communication in IEEE 802.11-basedMesh Networks. In *9th IEEE International Workshop on Factory Communication Systems (WFCS'2012)*, pp. 59–62, Lemgo, Germany, May 2012. `http://dx.doi.org/10.1109/WFCS.2012.6242541`

3. C. M. D. Viegas, F. Vasques. Real-Time Communication in IEEE 802.11 Wireless Mesh Networks: A Prospective Study. In *Proceedings of the 6th Doctoral Symposium in Informatics Engineering (DSIE'2011)*, pp. 251–262, Porto, Portugal, Jan. 2011. `http://paginas.fe.up.pt/~prodei/dsie11/images/pdfs/DSIE11ProceedingsWEB.pdf`

CHAPTER 1

Overview

This thesis intends to be a contribution for the advance of the state-of-the-art in real-time (RT) communication in IEEE 802.11s wireless mesh networks (WMNs). The premise of RT communication support in 802.11s WMNs is the ability to provide quality of service (QoS) support for time-constrained traffic. In this sense, this chapter presents an overview of the research context of this thesis, focusing on solutions for QoS provisioning in WMNs. The main challenges and impairments to support RT communication in WMNs are discussed, supporting the motivation for this work. Also, the objectives and major contributions for this thesis are outlined.

1.1 Research context and scope

Over the last few years, with the rapid growth of both Internet and wireless communications, the IEEE 802.11 family of wireless protocols has become the dominant solution for wireless local area networks (WLANs) implementations, due to its high performance, low cost and fast deployment characteristics [1–3].

In typical IEEE 802.11 WLANs deployment, wireless stations are either connected to an infrastructure (controlled by a central entity), or connected to each other forming an ad hoc topology (characterizing a distributed control). However, the traditional interconnection of multiple 802.11 WLANs rely on wired networks to carry out bridging functions. This dependency on wired infrastructure is costly, inflexible, and limits the coverage area, since the network cannot be extended beyond the backhaul deployment [4]. Moreover, centralized infrastructures are inefficient to support peer-to-peer applications, and fixed topologies do not provide redundancy on path selection, which inhibit stations from choosing a better path for communication [5]. Furthermore, although the ad hoc mode allows peer-to-peer communication, it does not provide any means to support multi-hop communication [6, 7].

Within this context, wireless mesh networks (WMNs) have emerged as a promising technology for next generation wireless networking, delivering wireless services for a large variety of applications. WMNs are decentralized, easy to deploy, and characterized by dynamic self-organization, self-configuration, and self-healing properties. In contrast to single-hop networks, where usually most of the traffic is directed to and received from a central infrastructure, WMNs, potentially, have no hierarchy. They provide greater flexibility, reliability and performance when compared to traditional WLANs. These characteristics enable the deployment of WMNs in several application domains, such as home, enterprise and industrial networks, transportation and real-time systems, building automation, and metropolitan area networks [8, 9].

In this sense, to overcome the limitations of mesh-like WLANs deployments, the IEEE 802.11s standard has been proposed to specify a WMN infrastructure over the traditional IEEE 802.11 WLANs. The IEEE 802.11s provides frame forwarding at medium access control (MAC) level, and extend the network coverage through a multi-hop wireless relaying backbone, where wireless nodes can relay traffic by traversing multiple hops throughout the network [10, 11]. Moreover, IEEE 802.11s-capable nodes are able to establish links with each other without being assigned specific roles or relying on a central entity to configure the mesh. In general, 802.11s WMNs are composed of: a) mesh routers, which are wireless nodes usually equipped with multiple radio interfaces, working as gateways/repeaters relaying traffic and interconnecting the network with other networks; and b) mesh clients, which usually have a single radio interface, able to relay traffic, but without gateway functions [9].

Recently, motivated by the advantages of WMNs over the traditional WLANs, the deployment of WMNs in industrial environments has become a research topic of interest. For instance, in industrial automation systems, wireless devices are a viable alternative to replace the current wired solutions, where real-time (RT) control applications may benefit from the improved network scalability, flexibility and mobility properties enabled by WMNs [3].

In such environments, RT traffic (typically small-sized messages) must be periodically transmitted among sensors, controllers, and actuators following strict transmission deadlines [12]. Commonly, RT services are classified as soft or hard real-time services, according to the deadline requirements of real-time applications. Soft real-time applications can tolerate some deadline misses, where performance is degraded, but not compromised by failing to meet the response time constraints. On the other hand, hard real-time applications require predictable and bounded response times, and any violation of these response times may lead to complete and catastrophic system failure [13].

The problem of real-time support consists of specifying, verifying and implementing communication systems that have predictable behavior to meet the temporal constraints imposed by the environment or by the user, even when the available resources are limited [13]. Real-time control applications usually are not resilient to delay and jitter constraints. In this sense, to support time-constrained traffic in WMNs deployed in industrial environments, real-time channels must be established according to specific traffic characteristics and to a set of quality of service (QoS) requirements.

The QoS term is referred as a set of service differentiation requirements to be supported by the network while transmitting data frames. These requirements, often known as QoS metrics, comprise throughput, delay, inter-packet delay variation (jitter), frame losses and deadline misses. Different applications may have different requirements for QoS metrics according to its traffic characteristics. The traffic characteristics comprise the identification of the traffic types, such as being sensitive to delays and/or losses, or bandwidth intensive, and if they comprise periodic or aperiodic tasks. This traffic characterization is important to provide the appropriate handling according to its requirements. The required service differentiation can be achieved by providing dedicated bandwidth for critical applications, controlling end-to-end delay, jitter, frame losses and deadline misses, managing and reducing network congestion, shaping network traffic to smooth the traffic flows, and/or setting transmission priorities according to the traffic type [14].

The first attempt to support QoS in a standardized fashion was through the IEEE 802.1D specification for Ethernet-based local area networks (LANs), which defines a protocol architecture for MAC-level bridges [15]. The 802.1D specification implements a traffic-handling policy within bridged LANs, by providing guidance on mapping user-application priorities into traffic classes. Traffic classes comprise multiple queues with specific access delays. The goal of these traffic classes is to support time-critical traffic, such as voice and video, by providing service differentiation according to the traffic type [16].

However, traffic classification by means of priority queues, by itself, is not enough to support the required QoS for RT traffic in wireless mesh networks. QoS provisioning in WMNs is far more challenging than in wired networks due to several difficulties associated with these networks. The most relevant challenges and impairments regarding the QoS provisioning in WMNs are summarized as follows [17–21]:

a) Error-prone wireless channels – The non-deterministic nature of wireless channels make them unreliable, since, beyond the multi-path fading effects [22], the communication is prone to interferences from other transmissions within the carrier sense range. When considering a multi-hop communication scenario, this behavior has a severe impact on the end-to-end communication, which may lead to link failures, path selection issues, unpredictable delays, and may cause more frames to be dropped;

b) Multi-hop communication – Despite the advantages enabled by multi-hop communication, it has severe impact over the throughput capacity, since the network throughput quickly degrades as long as the number of hops increase. Moreover, multi-hop scenarios exacerbate the hidden and exposed terminal problems. The hidden terminal problem occurs when a station is able to receive the signal from two different neighbors, but those neighbors cannot detect the signal of each other. On the other hand, exposed terminal problem occurs when a station is prevented from transmitting due to a neighboring transmitter. The hidden terminal problem is known to degrade the throughput due to collisions, while the exposed terminal problem results in poor performance by wasting concurrent transmission opportunities [23]. Furthermore, the current medium access control schemes of 802.11-based networks have been designed to single-hop scenarios, therefore they are not well-suited for multi-hop scenarios, specifically when dealing with concurrent channel access;

c) Lack of centralized control – The wireless stations access the channel in a distributed manner in WMNs. There is no centralized entity taking the responsibility of controlling channel access, to allocate dedicated resources or to disseminate reservation control information. This may lead to the difficulty of calculating and guaranteeing delay bounds required for real-time communication, where the stations must take decisions based on a local view of the network resources, resulting in potential inaccuracies;

d) Channel access contention and collision resolution – As the wireless channel is a shared resource and there is no central entity to control it, the nodes must contend for channel access opportunities. The channel access in 802.11-based wireless networks relies on carrier sense multiple access with collision avoidance (CSMA/CA), where nodes must listen before transmit. However, two nodes may sense the channel idle at same time and start transmitting simultaneously, resulting in a collision. Whenever a collision occurs, a non-deterministic backoff timer is employed for collision resolution. This collision resolution approach affects the fairness in channel access, the network throughput, and is also prone to unpredictable delays. Moreover, the MAC schemes of 802.11-based networks present a priority inversion problem, where high-priority traffic may face longer backoff times than low-priority traffic, this way delaying access and degrading the QoS for high-priority traffic, therefore favoring the channel access to low-priority traffic;

e) Limited resources availability – Due to the wireless communication properties, resources such as bandwidth and energy are limited. Moreover, most of the devices used in WMNs deployments are commonly equipped with a single radio interface, limiting the network communication capacity to single channel only. In single channel deployments, channel access opportunities may be scarce under high traffic loads, leading to increased delays and frame losses. Multi-channel capability allows to mitigate these issues by allocating different channels for communication, therefore alleviating the traffic load and increasing the performance [24];

f) Nodes mobility and dynamic topology – Nodes in WMNs may possibly move, leading to path failures, increased communication delays due to the reassociation process, and also causing QoS assurance violations. For instance, data sessions that have been admitted based on a certain level of available channel access time, may be starved of transmission opportunities after the reassociation. In addition, nodes may move to the carrier sense range of another nodes, thereby causing interferences, and increasing channel access delays, and transmission errors. Furthermore, due to energy constraints, battery-powered devices may randomly have their battery exhausted, leading to topology changes, and possibly requiring the renegotiation of QoS metrics;

g) Network heterogeneity – Mesh routers may considerably differ from mesh clients in terms of mobility and radio capabilities, and resources availability. Moreover, there are multiple traffic types, having different characteristics (e.g., size, deadline, generation distribution) and QoS requirements;

h) Path selection and links formation – Control frames are used for the purpose of multi-hop path discovery and selection, and links formation in WMNs. By default, the MAC mechanisms handle these control frames equally to data frames in terms of transmission priority, i.e. they are subject to channel contention, collisions, queue delays, and also interferences from concurrent transmissions. The lack of an adequate service differentiation for control frames leads to communication performance issues, such as path selection and links instability, and also increased end-to-end delays;

i) Multiple QoS requirements – Applications may have different QoS requirements, such as low jitter, increased throughput, reduced frame losses and strict deadlines, making it difficult to develop a unique QoS solution to meet all the requirements at once;

j) Network size – A higher number of nodes in the network generates a significant overhead related to the mesh discovery, formation and maintenance, which may impact on the overall communication performance, such as increased end-to-end delay and frame losses, and reduced throughput capacity.

The aforementioned challenges and impairments have motivated the quest for QoS solutions in wireless mesh networks. Although some of the problems have been addressed by the QoS models proposed in the literature, many of the impairments remain unresolved.

For instance, the increasing popularity of IP-based networks, specially driven by the evolution of Internet applications, such as streaming video and voice over IP (VoIP), motivated the search for adequate means to provide service differentiation in addition to the best effort service (i.e. the most common traffic delivery service provided in IP-based networks). The best effort service does not provide any bounds on delay, since all packets have equal transmission priority, and the network is not able to provide any packet delivery guarantees [25, p. 26, 107].

Seeking to enable the end-to-end QoS provisioning in IP-based networks, the internet engineering task force (IETF) has defined the integrated services (IntServ) [26] and differentiated services (DiffServ) [27] architectures. The IntServ follows a signaled-QoS model, in which the end-hosts announce their QoS requirements to the network, while the DiffServ follows a provisioned-QoS model, in which multiple traffic classes with varying QoS requirements are provided by the network elements [28].

However, when considering mobility in wireless mesh networks, neither IntServ nor DiffServ are able to adequately deal with mobile nodes. In IntServ, resources previously reserved to links along data paths may not be available wherever the mobile node may roam.

Likewise, in DiffServ, the service agreement level previously negotiated may be violated while the mobile node is moving, resulting in degraded QoS provisioning [25, p. 281].

Regarding the IEEE 802.11s WMN standard, the major difficulty to provide QoS guarantees is related to the inefficiency of medium access control (MAC) mechanisms. The IEEE 802.11s adopts the enhanced distributed channel access (EDCA) scheme as the main MAC mechanism, which relies on CSMA/CA to control the channel access, with a backoff scheme for collision resolution. EDCA provides traffic differentiation by means of four transmit queues with different priorities (derived from the user-application priorities of 802.1D). Despite the EDCA has been widely studied in the literature, where several research efforts targeted its evaluation regarding QoS provisioning capability [29–34], and some enhancements regarding contention issues [35–39], it still presents relevant impairments related to the channel access contention and collisions, unfair channel usage, and priority inversion on channel access under high traffic loads [40–42].

Moreover, IEEE 802.11s specifies an optional MAC mechanism called MCF controlled channel access (MCCA), which operates alongside EDCA on channel access control. MCCA has been proposed as a collision-free and guaranteed channel access for QoS-aware traffic during reserved periods. MCCA allows mesh stations to access the channel during predefined intervals with lower contention parameters. This way, the stations transmitting prioritized traffic experiences no competition from other stations on channel access. However, despite the increased communication performance, the MCCA scheme is not mandatory to all mesh stations. It might be used by a subset of mesh stations, where the communication performance may be affected by the channel contention of non-MCCA mesh stations [43, 44]. Moreover, the MCCA was designed to only perform reservations among adjacent mesh stations (i.e. single-hop reservations), and therefore, by default, it is not able to provide end-to-end QoS guarantees, being restricted to per-link QoS provisioning.

Recently, the IEEE 802.11ae [45] and 802.11aa [46] amendments have been proposed to improve QoS provisioning capability of IEEE 802.11 MAC sublayer. Commonly, control frames used for the network management are transmitted in the same EDCA priority queue as data frames, and therefore they are subject to queue delays and collisions. Seeking to alleviate these impairments, the 802.11ae introduces the QoS management frame (QMF) mechanism, which specifies the directives of service differentiation for control frames. Under the QMF policy, specific control frames are defined to be transmitted at different EDCA priority queues. For instance, control frames related to QoS signaling, (re)association process, beaconing, congestion control, path selection, and others, are transmitted in the voice queue (highest priority), while some minor control frames related to probing and mesh control are transmitted in the best effort queue.

Regarding the 802.11aa, it introduces a set of mechanisms for robust audio–video streaming. The mechanisms target the improvement of the transport of multimedia streams by introducing a stream classification service, which aims at providing intra-queue prioritization, a management scheme for cooperative sharing of the medium among APs that operate in the same channel and that are able to receive frames from each other, and a group addressed transmission service, which provides an efficient way to transmit multicast traffic to a group of stations.

Despite the improvements provided by both amendments to the 802.11 MAC sublayer [47], they still do not address the problem of unpredictable channel access delays due to contention, and also do not specify any means to control the interferences from concurrent transmissions.

Within this context, most of the aforementioned impairments on QoS provisioning in 802.11s WMNs are related to the inability of MAC mechanisms to support efficient channel access control. Although collective efforts of multiple layers of 802.11 protocol stack for QoS provisioning, the MAC sublayer is the most important among them, since it is responsible for channel access control and network resources management, which are key part to provide QoS guarantees. Moreover, the MAC sublayer handles the additional challenges for QoS provisioning, such as service differentiation, minimum delay and jitter guarantees, fairness management in channel usage, bandwidth allocation, and path selection.

This way, to support real-time communication in WMNs it is necessary to provide additional means to improve the medium access control mechanisms. For this purpose, the MAC mechanisms of 802.11s WMN standard must be aided by robust QoS solutions, such as resource reservation, admission and congestion control, rate adaptation and multi-channel capability.

Resource reservation consists of ensuring that real-time traffic may obtain the required network resources to meet its QoS requirements. RT traffic may benefit from the reservation in advance of dedicated links and channels, bandwidth, and channel access opportunities through time slots allocation. Reservations may help to maintain the required upper bounds for delay, jitter, and ratios of frame losses and deadline misses. Moreover, resource reservation schemes are able to mitigate the unpredictable channel access delays, to reduce the collision probability, and also to provide fairness in channel usage.

Resources can usually be reserved by QoS signaling [48, 49], in which the stations explicitly negotiate the QoS parameters by exchanging control frames for the purpose, by QoS routing [24, 50, 51], in which dedicated paths or channels are reserved for RT transmission, and by MAC scheduling [52–54], in which time slots or bandwidth are reserved and scheduled according to the QoS requirements of RT traffic.

Commonly, resource reservation may be coupled with admission control in order to improve resource management throughout the network. Admission control aims to estimate and control the state of the network resources, and thereby to decide which application data message streams can be admitted without harming the reserved resources of previously admitted message streams. Admission control may employ traffic policing and shaping schemes to limit the amount of incoming traffic in the network according to a certain profile [55]. Often, admission control may be based on bandwidth estimation [56–58], and link transmission cost [59].

Other elements such as the rate and congestion controls can also be operated in an resource reservation scheme. They can tune traffic volume in order to alleviate the issue of medium contention, to reduce interferences, to guarantee a fair channel usage, and also to prevent the starvation of network resources [18, 60]. Moreover, wireless mesh nodes equipped with multiple radio interfaces may benefit from the communication through multiple channels, where dedicated channels may be assigned to different radio interfaces in order to achieve efficient channel utilization, and minimize the contention periods and interferences [24, 61].

Within this context, this thesis investigates QoS provisioning techniques for real-time communication support in IEEE 802.11s WMNs. To mitigate the impairments related to the MAC mechanisms of 802.11s, this thesis proposes a resource reservation scheme, to deal with interferences in single channel WMNs, and to provide the required prioritization for real-time traffic. We consider a real-time communication environment, with a stationary topology limited by boundary wireless mesh stations. The incoming traffic is set to respect a set of QoS requirements defined by the real-time streams characteristics, such as periodicity (p_i) and deadline (d_i). The default medium access control (MAC) mechanism of 802.11s is aided by the reservation of time slots throughout the RT communication path, during which it is employed a slowdown contention policy able to reduce the surrounding interferences.

1.2 Objectives and motivation

The general objective of this thesis is to contribute for the advance of the state-of-the-art in real-time communication support in wireless mesh networks (WMNs), by studying, developing and evaluating efficient approaches for QoS provisioning in IEEE 802.11s WMNs.

Its main objective is to propose an efficient resource reservation scheme to support real-time communication in 802.11s WMNs. The purpose of resource reservation is to reserve network resources for time-constrained applications at mesh stations throughout the communication path, seeking to provide end-to-end QoS guarantees. Resource reservation schemes help to mitigate the unpredictable channel access delays, and to provide the adequate means to improve the communication reliability, by reducing the impact of interferences upon real-time communication.

As complementary objectives of this thesis, we highlight the following:

- To highlight new research directions through a comprehensive overview of the challenges and impairments in the field of QoS provisioning and RT communication support in 802.11s WMNs;
- To provide the major findings of an assessment of EDCA mechanism, highlighting the limitations to support RT traffic in multi-hop scenarios;

- To provide useful insights for the design and implementation of robust QoS schemes that improve the MAC mechanisms in WMNs, targeting the support of time-constrained traffic.

As motivation for this work, we highlight the following:

- The impairments related to the RT communication support in WMNs, such as the lack of a central infrastructure to control the channel access, unpredictable channel access delays due to contention, the multi-hop communication characteristics, and the interferences caused by concurrent transmissions;
- The inability of medium access control (MAC) mechanisms of 802.11s to provide adequate means for end-to-end QoS provisioning in multi-hop scenarios, when the wireless channel is shared with uncontrolled traffic sources;
- Most of the QoS solutions currently proposed in the literature still do not address relevant impairments for QoS provisioning in WMNs. For instance, adequate means to efficiently deal with interference of uncontrolled traffic sources in the network are still lacking.

These challenges and impairments have been the main motivation to propose a new resource reservation scheme to support RT communication in IEEE 802.11s WMNs.

1.3 Research questions and hypothesis

The research hypothesis foreseen for this thesis is that the support of RT communication in IEEE 802.11s WMNs is possible through improved QoS provisioning techniques. This hypothesis is supported by the following fundamental research questions:

Research question 1: *How important is QoS provisioning for real-time communication in IEEE 802.11s wireless mesh networks (WMNs)?*

QoS provisioning is a premise to support real-time communication in WMNs. QoS schemes provide the adequate means to mitigate the challenges and impairments related to the interferences and channel access control in WMNs, and to guarantee QoS requirements for real-time traffic, such as low end-to-end delay, jitter, and reduced ratios of frame losses and deadline misses.

Research question 2: *Which are the main challenges and impairments to support real-time communication in IEEE 802.11s WMNs?*

The main challenges and impairments to support real-time communication are related to the inability of medium access control (MAC) mechanisms to efficiently control the distributed channel access, and to provide the required QoS guarantees for time-constrained traffic in multi-hop communication scenarios. These impairments are responsible for the unpredictable channel access delays, and also for degraded ratios of frame losses and deadline misses, which severely impact on the real-time communication performance in WMNs.

Research question 3: *Which are the adequate means to improve the efficiency of QoS provisioning in 802.11s WMNs?*

The MAC mechanisms should be aided by robust QoS schemes to improve the efficiency of QoS provisioning in WMNs. Robust QoS schemes comprise resource reservation, admission and congestion control, rate adaptation and multi-channel capability. These schemes are able to improve the communication performance and reliability, by effectively mitigating the impairments and guaranteeing the QoS requirements of real-time traffic.

Based on these questions, we state that it is possible to improve the QoS provisioning for real-time communication support in IEEE 802.11s WMNs by aiding the MAC sublayer with the implementation of an adequate set of resource reservation schemes.

1.4 Methodology

The methodology adopted for this work is basically composed by the following three steps:

1. Literature review;
2. Assessment of the RT communication behavior of IEEE 802.11s WMNs standard;
3. Design and evaluation of a resource reservation scheme;
4. Assessment of the proposed resource reservation scheme, when supporting RT communication in 802.11s WMNs.

The literature review consisted of the study of the state-of-the-art in the context of real-time communication support and QoS provisioning in IEEE 802.11s WMNs. The objective of this study was to understand the characteristics of the current solutions available in the literature, and to identify the existing requirements, challenges and impairments. According to the literature review, the main impairments regarding the RT communication support in WMNs are related to the MAC mechanisms performance issues on multi-hop communication scenarios.

In this sense, seeking to evaluate the communication performance of the EDCA scheme (i.e. the main MAC mechanism of 802.11s), we devised and assessed a set of simulation scenarios.

These scenarios comprised an 802.11s wireless mesh network, where a set of nodes was defined to transmit real-time data streams, while another set was defined to transmit non-real-time data (i.e. interference traffic). The simulation experiments were performed using the network simulator 3 (ns-3) [62]. According to the simulation results, it could be observed that the RT communication behavior is severely affected by the presence of non-RT traffic sources. The EDCA mechanism, despite specifying service differentiation, is not able to adequately separate the higher priority traffic from the traffic transmitted at lower priority classes.

Motivated by the inefficiency of EDCA mechanism, we devised, implemented and assessed a resource reservation (RR) scheme to alleviate the impairments regarding the support of time-constrained traffic in 802.11s WMNs when the wireless channel is shared with uncontrolled traffic sources. This RR scheme, called mesh resource reservation (MRR), operates in the MAC sublayer of 802.11s by aiding the EDCA mechanism with the reservation of time intervals for channel access with reduced surrounding interferences. The effectiveness of the proposed scheme was assessed through an extensive set of simulations using the ns-3, and its performance was compared with the standard EDCA and MCCA MAC mechanisms, and also with another resource reservation scheme available in the literature, called distributed end-to-end allocation of time slots for real-time (DARE) [52].

1.5 Research contributions

The main contribution of this thesis is the proposal of the mesh resource reservation (MRR) scheme. The MRR scheme is a multi-hop RR scheme proposed to support real-time communication in IEEE 802.11s WMNs. This scheme is able to provide end-to-end QoS guarantees for real-time communication by reserving time intervals throughout an RT path, in which the RT traffic experiences less interferences. The effectiveness of the MRR scheme was demonstrated by an extensive set of simulations, where the results shown that it is possible to alleviate the impact of interferences upon real-time communication in multi-hop scenarios by means of resource reservation.

As a whole, the main contributions of this thesis were:

- A comprehensive study of the state-of-the-art on QoS provisioning in IEEE 802.11s WMNs, in which the main challenges and impairments to support real-time communication are identified and discussed. The major results from this study were published in: [63][64];
- An extensive evaluation of the capability of EDCA mechanism for QoS provisioning in WMNs, in which were demonstrated by simulation the impairments on supporting real-time communication, and also some useful hints are given on setting up the network parameters for improved communication performance of 802.11s WMNs. The major results from this work were published in: [40][41][42].

- The proposal and evaluation of MRR scheme, as well as a comparative assessment with MCCA and DARE schemes, regarding the support of RT communication in IEEE 802.11s WMNs. The results of this evaluation have been submitted for publication in: [65].

1.6 Thesis outline

Beyond this introductory overview, the remainder of this thesis is organized in five additional chapters, as follows:

Chapter 2 presents an overview of the IEEE 802.11s WMN standardization. An introduction to 802.11s standard is given, with a brief description of physical (PHY) specifications, and a more detailed description of medium access control (MAC) mechanisms. This overview provides the fundamental background for the work proposed in this thesis.

Chapter 3 presents a published book chapter [64] which discusses relevant aspects of RT communication support in 802.11-based wireless mesh networks. Relevant work on QoS provisioning is reviewed in the chapter, and some useful insights and future research directions related to the topic are discussed.

Chapter 4 presents a published paper [42] which assesses the IEEE 802.11s WMN standard regarding the RT communication support. The objective of this assessment was to evaluate the performance of EDCA mechanism to support time-constrained traffic when the wireless channel is shared with uncontrolled traffic sources. Through simulations, a set of real-time data streams were defined, and several communication scenarios with different interference loads were assessed. Furthermore, a sensitivity analysis of the network configuration parameters was performed, in order to provide useful hints on setting the channel contention and routing parameter values, aiming the reduction of interference impact upon RT communication. This assessment is of paramount importance to the design of new MAC schemes targeting the RT communication support in IEEE 802.11s WMNs.

Chapter 5 presents a paper submitted to a peer-review journal [65], where a new resource reservation scheme is proposed to support RT communication in 802.11s WMNs. The proposed scheme performs end-to-end reservations of time intervals, during which the neighboring stations of a real-time path contend for the channel in a slowdown contention mode. The objective of this scheme is to reduce the surrounding interferences over the real-time communication in order to meet the QoS requirements. The effectiveness of the proposed scheme is assessed through an extensive set of simulations, and it is compared with the MAC schemes defined by IEEE 802.11s and also with another resource reservation scheme available in the literature.

Finally, Chapter 6 presents the final considerations about this work, and some future work directions are also discussed.

CHAPTER 2

Background

This chapter provides the required background for this thesis, regarding the description of IEEE 802.11s wireless mesh network (WMN) standard. Initially, Section 2.1 presents the IEEE 802.11s WMN specification, by describing its main features and the elements related to the mesh formation and management. Since the IEEE 802.11s defines a layer 2 mesh infrastructure over the traditional 802.11 wireless local area networks (WLANs), it adopts the same physical (PHY) layer specification and MAC sublayer architecture of IEEE 802.11 standard. Thus, Section 2.2 presents a brief overview of the IEEE 802.11 PHY specification, and finally, Section 2.3 presents the main functionalities of MAC mechanisms, and discusses their QoS provisioning properties and limitations. Although the 802.11 family of standards has several amendments to its specification, this chapter is focused just on those related to quality of service (QoS) support and wireless mesh networks (WMNs).

2.1 IEEE 802.11s wireless mesh networking

The IEEE 802.11s standard specifies a wireless mesh network (WMN) infrastructure over the IEEE 802.11 WLANs. The objective is to extend the coverage of traditional WLANs by using a multi-hop wireless relaying backbone, and to allow the support of a larger diversity of wireless technologies. In traditional 802.11-based WLAN, an extended service set (ESS) is formed by a group of basic service sets (BSSs) interconnected through a wired distribution system (DS) based on IEEE 802.3 Ethernet. The way how the BSSs are interconnected leads to a poor scalability and increases the network costs.

The 802.11s wireless mesh networks enable the interconnection of multiple BSSs via a wireless DS, this way supporting a higher number of nodes, and thereby increasing the network scalability. Essentially, an 802.11s WMN is composed of several interconnected mesh stations (STAs), forming a mesh basic service set (MBSS). Each mesh STA may operate as a host (mesh client) or as a router (mesh STA), relaying frames on behalf of other mesh STAs that may or may not be within the transmission range, or may not have mesh capabilities. Figure 2.1 illustrates an example of an 802.11s WMN and its elements.

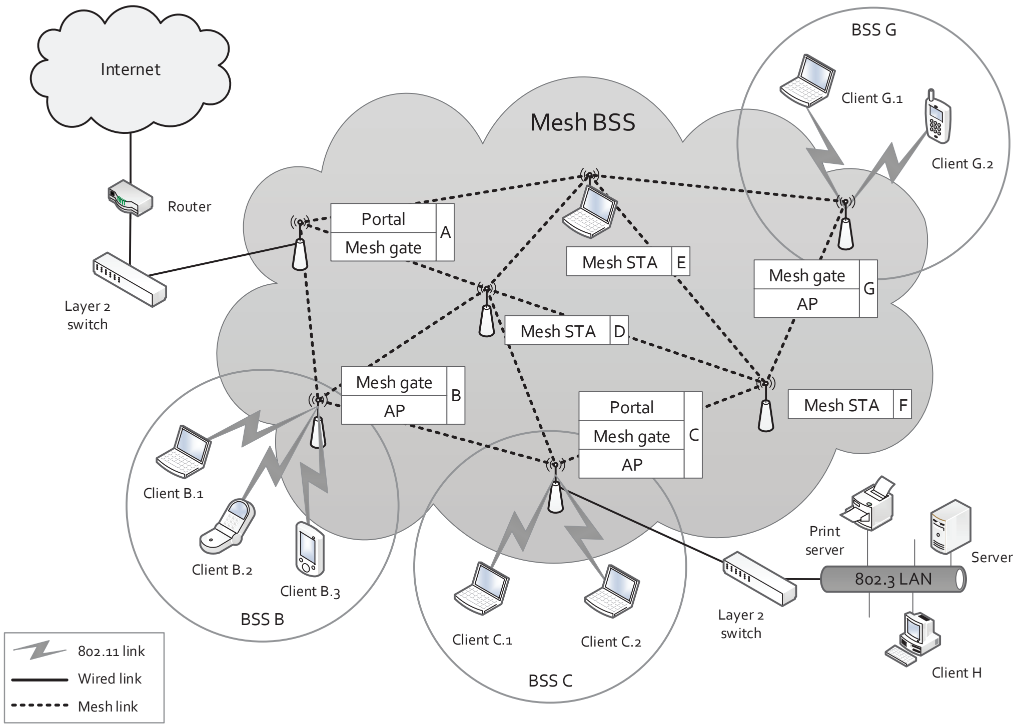

Figure 2.1 Elements of a IEEE 802.11s WMN.[a]

Regarding the example of Figure 2.1, several mesh STAs form an MBSS. Some mesh STAs have additional access point (AP) capabilities. A mesh STA AP collocated with mesh gates allows the interconnection of 802.11 legacy stations belonging to BSSs with the MBSS. For instance, although not being in the direct transmission range, the clients of BSS B are able to communicate with those of BSS G, via mesh APs B and G. Some other mesh STAs, in particular, can work as gateways between the MBSS and other 802-based networks (e.g. 802.3 LAN). These gateways, referred as portal nodes, enable the extension of the mesh network coverage, and also allow the interconnection of MBSS with one or more DSs. For example, client H may benefit from the access to Internet services through portal C, or clients of BSS C can access the printer server in an 802.3 LAN.

To enable all of those mesh capabilities, a set of modifications and functionalities have been introduced with the 802.11s specification. The next subsections present a detailed description of that set.

2.1.1 Addressing and mesh frame format

In order to enable multi-hop functions at the MAC sublayer, the IEEE 802.11s specification extends the original 802.11 frame format to support up to six MAC addresses [10]. The six addresses enable the support of communication among mesh stations and non-mesh stations, i.e. stations outside MBSS are allowed to participate in the mesh communication through a collocated mesh STA with portal functions (see Figure 2.2).

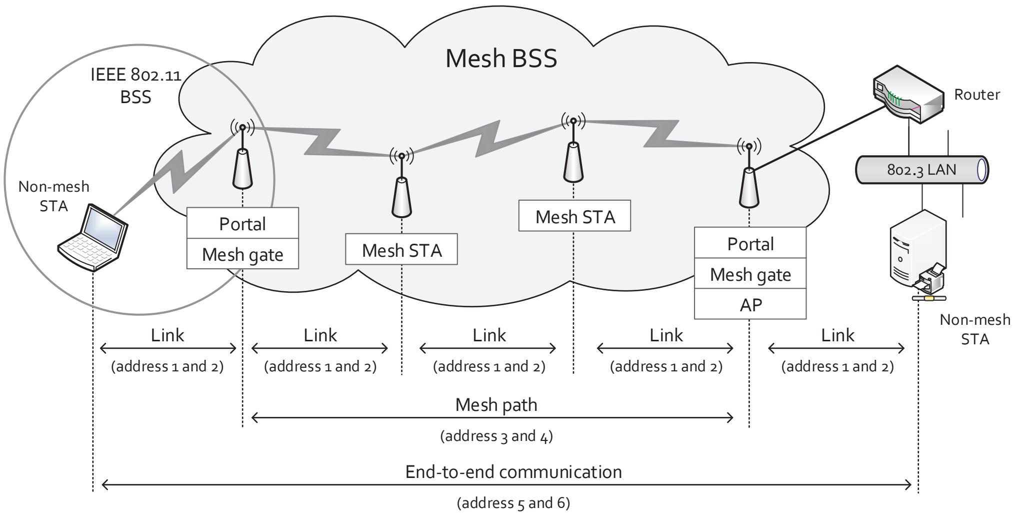

Figure 2.2 Example of end-to-end communication in 802.11s WMN.[b]

The six addresses are defined as follows:

1. Addresses 1 and 2 define the receiver address (RA) and transmitter address (TA), respectively;
2. Addresses 3 and 4 define the mesh destination address (mesh DA) and mesh source address (mesh SA), respectively. The mesh SA and mesh DA are the addresses of mesh gate STAs which are connected to the non-mesh STAs;
3. Addresses 5 and 6 define the destination address (DA) and source address (SA) of end-points in the communication, respectively.

Currently, 802.11 categorizes frames as data, control, or management. Data frames carry higher-layer data. Control frames are used for acknowledgments and reservations. Devices use management frames to set-up, organize, and maintain a WLAN and the local link. To enable mesh functions, 802.11s extends data and management frames by an additional mesh control field (see Figure 2.3). This mesh control field is included in the frame body, and consists of a mesh flags field, a mesh time to live (TTL) field, a mesh sequence number, and alternatively a mesh address extension field. The TTL and sequence number fields are used to prevent the frames from looping forever [5]. When mesh stations communicate over a single-hop, their frames do not carry the mesh control field. The mesh flags field indicates the presence of additional MAC addresses in the mesh control field. The address extension allows for a total of six address fields in a mesh frame.

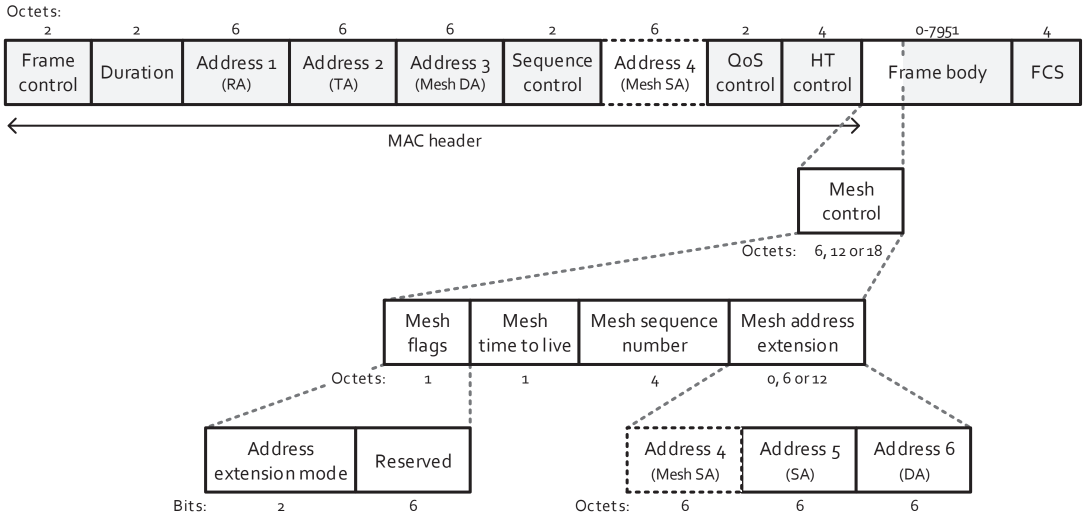

Figure 2.3 IEEE 802.11s frame format.[c]

It is worth noting that the address extension field allows for the addition of three addresses, rather than just two. The rationale for this is that standard management frames have three addresses only. Hence, in the case of multi-hop mesh management frames, address 4 is included in the mesh control field rather than in the standard frame header [5].

2.1.2 Mesh network establishment

The mesh establishment is performed by a station that passively or actively scans for existing mesh basic service sets (MBSSs). On passive scanning, a station passively overhears beacon frames transmitted in the neighborhood. On the other hand, on action scanning, stations actively sends probe requests and waits for probe responses. During the scanning phase, frames exchanged among stations must contain a mesh profile, in which MBSS formation attributes are specified. According to the scanning results, the stations should join any existing MBSS or creates a new one.

After finishing the scanning phase, the station (STA) shall establish peer-links with discovered mesh STAs in the neighborhood. A peer-link is required for direct communication among mesh STAs. Any discovered mesh STA is considered a candidate peer mesh STA for the intended MBSS. A candidate peer mesh STA is only admitted as mesh STA when the mesh peering management (MPM) protocol manages to establish peer-links among three mesh STAs, at least.

The MPM protocol is responsible to establish, manage and tear down mesh peer-links. Three special mesh peering frames are used for the purpose: *mesh peering open*, *mesh* *peering confirm* and *mesh peering close*. Figure 2.4 illustrates an example of a mesh peering establishment between a candidate station and a mesh STA which is member of an MBSS.

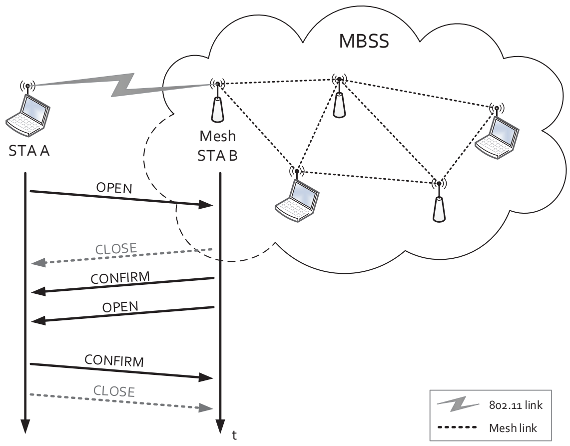

Figure 2.4 Mesh peering establishment procedure.

In the Figure 2.4, STA A is requesting to STA B the ingress on the MBSS. The peering establishment procedure starts with STA A sending a *mesh peering open* frame to STA B, requesting a link. A *retryTimer* is triggered in case of confirmation absence from STA B.

Upon reception of *open* frame, STA B sends a confirmation to STA A through a *mesh peer confirm* frame followed by a *mesh peer open*. A *confirmTimer* is triggered, which is used to indicate if a *confirm* frame was received by STA A. Then STA A, upon reception of *confirm* and *open* frames from STA B, sends a final *confirm* frame to STA B to finish the mesh peering establishment.

During the establishment procedure, if any STA disagree with the link formation, or if there is any failure during the data frames transmission, the mesh STA tears down the peer-link by sending a *mesh peering close* frame. When a *close* frame is sent, a *holdingTimer* is triggered to indicate that a peer-link must be closed.

2.1.3 Mesh path selection

The path selection on 802.11s WMNs is performed by the hybrid wireless mesh protocol (HWMP). HWMP combines reactive (on-demand) path selection with extensions to enable proactive (tree-based) path selection. The reactive mode is based on the ad hoc on-demand distance vector (AODV) routing protocol, which allows mesh STAs to communicate in a peer-to-peer basis. In the proactive mode additional tree building functionality is added to the reactive mode.

HWMP uses MAC addresses as a layer 2 forwarding protocol. Thus, HWMP is able to use enhanced metrics than the hop count, such as radio-aware metrics, being the airtime link the default HWMP metric. The airtime link metric is proposed for basic interoperability among IEEE 802.11s devices, and it reflects the amount of channel resources consumed during a test frame transmission over a particular link. The path with the smallest airtime link metric is considered to be the best forwarding path [66, pp. 133–136]. The airtime link metric is computed as follows:

$$C_a = \left[O + \frac{B_t}{r}\right] \cdot \frac{1}{1 - e_f}, \tag{2.1}$$

where O is a constant overhead latency that varies according to the PHY specification in use, B_t is the size of a test frame (1,024 bytes), r is the data rate in Mbps used by the mesh STA while transmitting the test frame, and e_f is the measured error rate of test frame [10].

During the path discovery process, each mesh STA in the network contributes to the metric calculation by using management frames to exchange routing information. The management frames are composed of information elements with specific purposes. Five information elements have been defined for HWMP operation, as follows:

1. Path request (PREQ): used for discovering a path to one or more target mesh STAs, maintaining a path, building a proactive (reverse) path selection tree to the root mesh STA, and confirming a path to a target mesh STA (optionally);
2. Path reply (PREP): used to establish a forward path to a target and to confirm that a target is reachable. The PREP is issued in response to a PREQ;
3. Path error (PERR): used for announcing an unreachable destination;
4. Root announcement (RANN): used for announcing the presence of a mesh STA configured as root mesh STA. RANN elements are sent out periodically by such a root mesh STA;
5. Gate announcement (GANN): used for announcing the presence of a mesh gate in the MBSS.

2.1.3.a Reactive path selection

In the reactive or on-demand mode, the path discovery process is only initiated when a mesh STA needs to find a path to a destination. In this case, the originator mesh STA broadcasts PREQ elements containing the destination address. Mesh STAs in the neighborhood, upon PREQ reception, create or update their path information to the originator, and propagate the PREQ element to their neighbors until reaching the destination mesh STA. If the destination is in the list of targets for that PREQ, the destination mesh STA sends a unicast PREP back to the originator. During the PREP transmission, the intermediate mesh STAs create a path to the destination upon PREP reception, and also forward that PREP to the originator. Once the originator receives the PREP element, the path with the intended destination is established.

The condition to update an existing path relies on the HWMP sequence number (SN) and the airtime link metric information sent in PREQ, RANN or PREP elements. Upon a PREQ/PREP/RANN element reception, the mesh STA checks the current path to destination and if it has lower HWMP SN and/or metric values, it is updated with the information from the current received element.

2.1.3.b Proactive path selection

In the proactive mode, additional tree building functionality is added to the reactive mode. A mesh STA is configured as the root of a path tree (formally root mesh STA), which is responsible to coordinate the path selection. Two mechanisms are used to proactively disseminate the mesh root STA information across the MBSS.

The first method relies on proactive PREQ elements to create a path among all mesh STAs and the root mesh STA. In this method, the root mesh STA periodically broadcasts PREQ elements to the mesh STAs in the neighborhood. Upon reception of a PREQ, a mesh STA creates or updates its forwarding information to reach the root mesh STA, updates the metric and hop count of the PREQ, records the metric and hop count, and then transmits the updated PREQ. Thus, the distance vector to root can be disseminated to all mesh STAs in the network.

The second method relies on RANN elements to distribute the path information for reaching the root mesh STA, but no forwarding information is created. The root periodically broadcasts RANN elements to all mesh STAs. The information contained in the RANN elements is used to disseminate path metrics to other mesh STAs to reach root mesh STA, but the reception of RANN does not establish a path. Upon reception of a RANN, each mesh STA that has to create or update a path to the root mesh STA sends an individually addressed PREQ to the root mesh STA via the mesh STA from which it received the RANN. When the root receives this PREQ, it replies with a PREP to the mesh STA. Thus, the individually addressed PREQ creates the reverse path from the root mesh STA to the originator mesh STA, while the PREP creates the forward path from the mesh STA to the root mesh STA.

Moreover, the GANN element is used to announce the presence of a mesh gate in the mesh BSS. Gate announcements allow mesh STAs to discover such a mesh gate and, if necessary, to build a path towards it. This process is similar to the RANN in its logic and behavior, announcing the gate instead of the root.

2.2 IEEE 802.11 PHY overview

Currently, the 802.11 family of standards comprises seven over-the-air PHY specifications, where all share the same layer 2 protocols. The first IEEE 802.11 standard (legacy) was proposed in 1997 and it specifies the PHY and MAC layers to meet the requirements for WLANs standardization. Three specifications for the PHY layer were initially defined: frequency hoping spread spectrum (FHSS), direct sequence spread spectrum (DSSS) and infrared, reaching data rates of up to 2 Mbps. The first two specifications operate in the 2.4 GHz industrial scientific and medical (ISM) unlicensed frequency band, while the latter uses the infrared band with wavelengths ranging from 850 to 950 nm. However, the data rates achieved by these first PHY specifications were rather limited, therefore conditioning their usage for applications which demanded higher data rates.

In 1999, seeking to improve the data rates of the legacy standard, the IEEE working group introduced two new PHY specifications, namely the IEEE 802.11a and IEEE 802.11b. The 802.11a operates in the 5 GHz frequency band, based on orthogonal frequency-division multiplexing (OFDM) with BPSK, QPSK, 16-QAM or 64-QAM modulations, reaching data rates of up to 54 Mbps, whereas the 802.11b operates in the 2.4 GHz frequency band, based on high rate direct sequence spread spectrum (HR/DSSS) with complementary code keying (CCK) modulation, reaching data rates of up to 11 Mbps.

While it was expected to use either standards depending on the data rates required by the applications, the WLAN market based on 5 GHz band was not fully utilized due to the high cost of radio frequency (RF) implementation in the early 2000's [67]. On the other hand, there was a demand for even higher data rates at 2.4 GHz frequency band. Thus, in 2003, the IEEE 802.11g was released as an extension to the 802.11b specification. This new extension uses the extended rate PHY OFDM (ERP-OFDM) with the same modulation techniques of 802.11a, reaching data rates of up to 54 Mbps in 2.4 GHz frequency band. The 802.11g was widely accepted by the market, where for some time it was regarded as the *de facto* standard to implement wireless networking.

With the widespread of broadband Internet services, an increasing demand for even higher data rates has not ceased. Thus, in 2009, the IEEE 802.11n specification was proposed to maximize the network throughput capacity. This specification operates in both 2.4 and 5 GHz bands, based on single-user multiple-input/multiple-output (SU-MIMO)-OFDM. The MIMO technique allows a single radio channel to support the transmission of multiple data streams [68]. It is worth noting that the previous PHY specifications relied on single-input/single-output (SISO) technique, which allows the transmission of a single data stream. Beyond the capabilities offered by MIMO, the communication speed can be increased by doubling the channel width from 20 MHz to 40 MHz, thereby enabling devices to reach data rates of up to 600 Mbps. Moreover, the 802.11n introduces frame aggregation properties to the MAC sublayer, and defines the block acknowledgment scheme as mandatory. The core idea behind aggregation is that by forming an aggregate frame, the overhead and channel contention delays are reduced. Currently, the 802.11n standard is the most capable in providing higher data rates at 2.4 GHz RF band.

Following the trend of maximizing the network throughput, the 802.11 working group started the very high throughput (VHT) study group to create even faster wireless

Table 2.1 Comparative chart among IEEE 802.11 PHY specification.

802.11 PHY	Release date	RF band (GHz)	Channel width (MHz)	Multiplexing technique	Spatial streams	Modulation	Theoretical max. data rate (Mbps)
legacy	1997	2.4	22	FHSS, DSSS	1	GFSK (FHSS) BPSK, QPSK (DSSS)	2
a	1999	5	20	OFDM	1	BPSK, QPSK, 16-QAM, 64-QAM	54
b	1999	2.4	22	HR/DSSS	1	CCK	11
g	2003	2.4	20	ERP-OFDM	1	BPSK, QPSK, 16-QAM, 64-QAM	54
n	2009	2.4, 5	20, 40	OFDM (SU-MIMO)	up to 4	BPSK, QPSK, 16-QAM, 64-QAM	600
ad	2012	60	2,160	OFDM, Single carrier	1	BPSK, QPSK, 16-QAM, 64-QAM	6,756
ac	2013	5	20, 40, 80, 80+80, 160	OFDM (MU-MIMO)	up to 8	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	6,933

networking [69]. In 2012, the VHT group introduced the multi-gigabit 802.11ad specification operating in the unlicensed RF band of 60 GHz, with four wide channels of 2,160 MHz each. In contrast to the 802.11n, which is based on MIMO, the 802.11ad is based on SISO technique. 802.11ad defines a single carrier modulation (for low-powered devices) with BPSK, QPSK and 16-QAM coding schemes, reaching data rates of up to 4.620 Gbps, and in addition it uses OFDM with BPSK, QPSK and 64-QAM modulations, reaching data rates of up to 6.756 Gbps. Despite achieving higher data rates, the signal attenuation at 60 GHz is very high, and typically cannot penetrate walls, therefore restricting the application of 802.11ad standard [70]. Key applications of 802.11ad are point-to-point and outdoor applications using highly-directional antennas.

Due to the RF limitations at 60 GHz, in 2013, the VHT study group has introduced the IEEE 802.11ac specification, operating at 5 GHz RF band, and based on multi-user multiple-input/multiple-output (MU-MIMO) OFDM. MU-MIMO enables better spatial reuse by allowing the signal transmission and reception from multiple devices in the same RF band simultaneously. The communication throughput is increased by using channel width of 80 MHz, which doubles the size of the spectral channel over 802.11n. Moreover, for even higher speeds, the specification defines wider channels of 160 MHz. However, due to the limitation to find contiguous 160 MHz spectrum, the standard allows for a 160 MHz channel to be either a single contiguous block or two non-contiguous 80 MHz channels (80+80 MHz) [69]. The 802.11ac is able to reach data rates of up to 6,933 Mbps when using up to eight spatial streams. Currently, the 802.11ac standard is elected as a potential successor of 802.11n.

To summarize the previously described 802.11 PHY specification, Table 2.1 presents a brief comparison among IEEE 802.11 standard characteristics.

Driven by the rapidly increasing demand for high data rate services and usage in a spectrum of application areas, the IEEE 802.11 standards are compelled to evolve in order to meet the performance requirements in terms of spectral efficiency, coverage, latency, and energy efficiency [71]. Thus, newer specifications are continuously being devised to meet these performance requirements in a near future [72].

2.3 Medium access control

The medium access control (MAC) sublayer provides addressing and channel access control mechanisms that allow communication among devices in a shared medium. A MAC mechanism works as a scheduling algorithm which allocates the channel to stations during specific periods. The IEEE 802.11 family of standards defines a set of MAC mechanisms, which can be classified into distributed mechanisms, which do not rely on any central infrastructure, and centralized mechanisms, where the channel access is coordinated by a central entity [11].

As an amendment to the 802.11 WLANs, the IEEE 802.11s WMN standard adopts the same PHY and MAC specifications, with additional functions to the latter. The MAC sublayer architecture of IEEE 802.11 comprises four coordination functions:

1. Distributed coordination function (DCF): required for contention services, being the basis for all other coordination functions;
2. Point coordination function (PCF): required for contention-free services;
3. Hybrid coordination function (HCF): required for parameterized QoS services;
4. Mesh coordination function (MCF): required for controlled mesh services.

A representation of MAC sublayer architecture is depicted in the Figure 2.5.

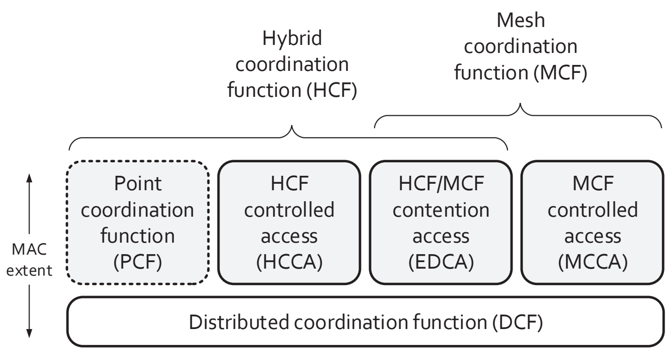

Figure 2.5 IEEE 802.11 MAC architecture.[d]

2.3.1 Distributed coordination function

The distributed coordination function (DCF) is the fundamental MAC mechanism of IEEE 802.11. It relies on the CSMA/CA technique for channel access. The CSMA starts with a station sensing the medium before transmitting (carrier sense). If a station willing to transmit senses the medium idle for at least a DCF interframe space (DIFS) period, it can start transmitting its frames, and all other stations must wait until the medium becomes idle again. Otherwise, if a station senses the medium busy, a backoff period is initiated by that station to avoid collisions. This backoff period determines how long a station must wait before sensing the medium again.

The backoff period is a uniformly distributed value between zero and the size of contention window (CW). At each unsuccessful transmission, this period is increased by $(2 \times \mathrm{CW} + 1)$, growing exponentially until reaching the maximum CW value. Once a station has started its backoff period, it is decremented at each slot time. If the medium becomes busy again during the backoff period, all the stations performing backoff pause the countdown procedure. The paused backoff is resumed only when the medium is sensed idle again for a DIFS period. Thus, a station is only able to transmit frames when its backoff period reaches zero.

In addition to the backoff scheme, the CSMA/CA may optionally be complemented by the request to send (RTS) and clear to send (CTS) control frames (see Figure 2.6), in order to reduce frame collisions introduced by the hidden terminal problem. The hidden terminal problem occurs when a station is able to receive the signal from two different neighbors, but those neighbors cannot detect the signal of each other.

When a transmitter needs to send data, it requests the medium by sending an RTS control frame and waits for a response from the receiver in form of a CTS control frame, which confirms the idle medium. If a CTS frame is not received after an RTS frame, the transmitter starts a backoff period.

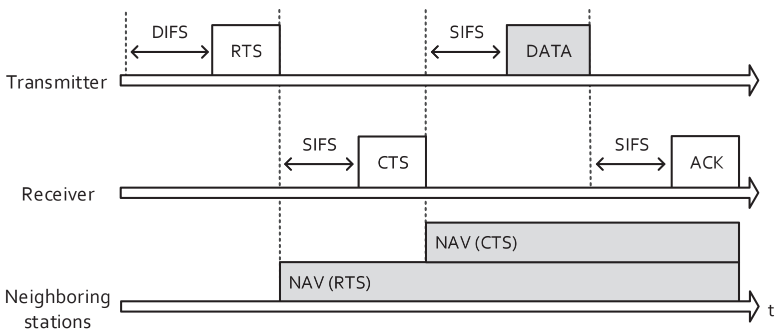

Figure 2.6 RTS/CTS mechanism example.[e]

Upon receiving RTS/CTS frames, the stations in the neighborhood set their network allocation vector (NAV). This NAV is a timer during which the stations in the neighborhood abstain from transmission, enhancing the protection of the requested transmission.

Regarding the QoS provisioning, the DCF scheme has some limitations. It only provides best effort services, where the packets are simply discarded when the queue is full. Moreover, there are no traffic differentiation schemes to separate traffic according to its priorities. Under high traffic loads, the DCF presents considerable performance degradation, since all the stations must compete for the medium with the same priority [73].

2.3.2 Point coordination function

The point coordination function (PCF) is an optional MAC mechanism that uses a polling scheme controlled by the point coordinator (PC) operating at the access point (AP). The PC is used to determine which station is assigned the right to transmit. This mechanism can only be used in infrastructure network configurations, where stations are connected to the AP. The PCF function controls the medium access during the contention free period (CFP), where the PC sends contention-free-poll (CF-Poll) frames to each station, one at a time, to give them the opportunity to transmit, and alternates with the contention period (CP), where the DCF takes control.

Despite its specification in the 802.11s standard, the PCF mechanism has not been commercially implemented. Therefore, we opt to not detail the PCF functionalities. Moreover, regarding the QoS support, the PCF is not able to handle multiple QoS requirements of different traffic types, because it defines only a round-robin scheduling algorithm. Furthermore, the AP contends for the channel access with the same priority of other stations in order to transmit the beacon frame, causing delays, and, thereby, decreasing the network performance [73, 74].

2.3.3 Hybrid coordination function

The hybrid coordination function (HCF) was introduced by the IEEE 802.11e specification. The IEEE 802.11e has been developed to introduce traffic differentiation at MAC level, motivated by the impairments of DCF and PCF regarding QoS provisioning. HCF comprises two new medium access mechanisms which combine aspects of DCF and PCF with improvements to provide service differentiation: the enhanced distributed channel access (EDCA), which is a contention-based mechanism proposed to enhance the DCF, and the HCF controlled access (HCCA), which is a controlled access mechanism proposed to enhance the PCF. The coordination of both mechanisms is performed by the hybrid coordinator (HC), operating at access point [11]. Moreover, the HCF introduces the concept of transmission opportunity (TXOP), which is an interval during which the stations have the opportunity to transmit data. The TXOP concept aims to solve the transmission timing issues and unpredictable delays, by improving the medium usage fairness.

2.3.3.a Enhanced distributed channel access

The enhanced distributed channel access (EDCA) mechanism provides service differentiation by classifying multiple traffic flows into access categories (ACs). Four access categories are defined, in which frames of different traffic types are mapped according to the QoS requirements. These ACs are derived from the eight user priority (UP) levels introduced by IEEE 802.1D specification [15], and consist of background (BK), best effort (BE), video (VI) and voice (VO) traffic classes (see Table 2.2).

Table 2.2 User priority mapping according to access categories.

Priority	UP	802.1D designation	Access category	Designation
Lower	1	Background (BK)	AC_BK	Background
	2	—	AC_BK	Background
	0	Best effort (BE)	AC_BE	Best effort
	3	Excellent effort (EE)	AC_BE	Best effort
	4	Controlled load (CL)	AC_VI	Video
	5	Video (VI)	AC_VI	Video
	6	Voice (VO)	AC_VO	Voice
Higher	7	Network control (NC)	AC_VO	Voice

To understand the mapping presented in Table 2.2, we need to consider the types of traffic that are associated with each access category. In descending priority order, these types include [16, 75]:

- Network control (7): both time- and safety-critical, consisting of traffic needed to maintain and support the network infrastructure;
- Voice (6): time-critical, characterized by less than 10 ms delay;
- Video (5): time-critical, characterized by less than 100 ms delay;
- Controlled load (4): non-time-critical, but loss sensitive, such as streaming multimedia and business-critical traffic; typically used for applications that require reservation or admission control;
- Excellent effort (3): also non-time-critical, but loss sensitive; for best-effort services delivered to the most important customers;
- Best effort (0): non-time-critical and loss insensitive. This is the most common service provided by traditional networking;
- Background (1): non-time-critical and loss insensitive, but of lower priority than best effort; includes bulk transfers and other data transfer that are permitted on the network, but that should not impact the use of the network by other users and applications.

For each AC, an enhanced variant of DCF mechanism, called EDCA function (EDCAF), contends for TXOPs using individual contention parameter values. These contention parameters comprise a variable interframe space, called arbitration interframe space (AIFS), and multiple contention window (CW) sizes. Table 2.3 presents these contention parameter values for each AC.

Table 2.3 Default DCF and EDCA parameter set.

MAC	**AC**	**CW_{min}**	**CW_{max}**	**AIFSN** (inside BSS)	**AIFSN** (outside BSS)	**DIFS**
DCF	—	aCW_{min}	aCW_{max}	—	—	2
EDCA	AC_BK	aCW_{min}	aCW_{max}	7	9	—
	AC_BE	aCW_{min}	aCW_{max}	3	6	—
	AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}	2	3	—
	AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2	2	—

The values for aCW_{min} and aCW_{max} are defined according to the PHY specification in use. For instance, the IEEE 802.11a/g/n/ad/ac specifications define these values as 15 and 1,023, respectively, and the IEEE 802.11b specification defines as 31 and 1,023, respectively [11].

Each AC works as a priority queue, where the highest priority categories wait a smaller AIFS period to access the channel, have smaller CW to perform backoff, and can occupy the channel for longer (i.e. have a higher TXOP), while in the lowest priority categories, the opposite occurs. Figure 2.7 illustrates the architecture of EDCA mechanism and its transmit queues.

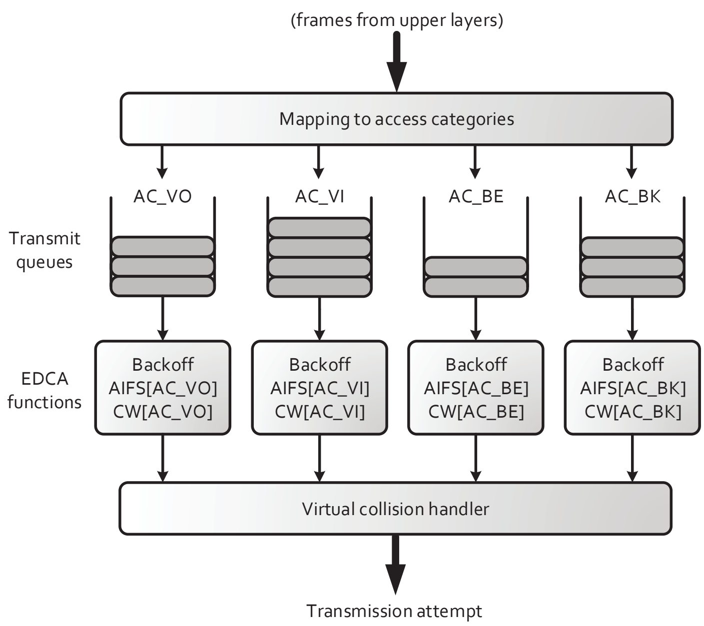

Figure 2.7 EDCA transmit queues model in IEEE 802.11e.[f]

During the contention period, each station senses the medium in order to start transmitting. If the medium is sensed idle for at least one AIFS[AC] period, the station transmits its frames. Otherwise, the station initiates a backoff period in order to avoid collisions. The duration of AIFS[AC] is computed as follows:

$$\text{AIFS[AC]} = \text{AIFSN[AC]} \times \text{aSlotTime} + \text{aSIFSTime} \tag{2.2}$$

where AIFSN[AC] defines the number of slot times per AC (where AIFSN[AC] ≥ 2), aSlotTime is the minimum slot duration defined according to the PHY specification in use, and aSIFSTime is the short interframe space (SIFS) period. To understand the effects of each set of contention parameter values, Figure 2.8 illustrates the channel access behavior per AC.

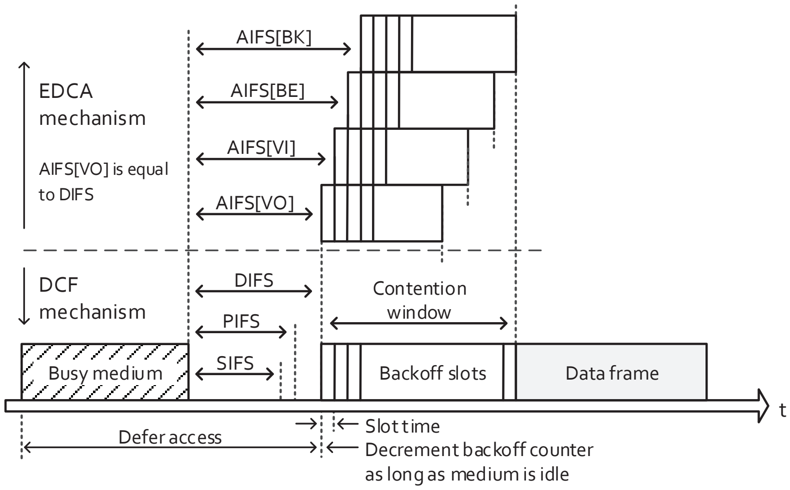

Figure 2.8 Channel access behavior according to the contention parameters of each EDCA access category.[g]

2.3.3.b HCF controlled access

The HCF controlled access (HCCA) is a contention-free mechanism, which, similarly to PCF, uses a polling scheme managed by the hybrid coordinator (HC), located in the access point (AP). The HC is responsible to perform the traffic admission control and to assign TXOPs to the stations during the controlled access phase (CAP). For channel access during the CAP, each station must send an admission request to the HC, containing the traffic specification (TSPEC) of each data flow. The TSPEC is a set of parameters that define the characteristics and QoS requirements of a flow. If the negotiated TSPEC can be admitted by the HC, a TXOP is given to the station in order to transmit its flows [11].

The HCCA is not implemented by the 802.11s standard (as it is based in a centralized MAC scheme), and, therefore, we opt to not detail the mechanism operation.

2.3.4 Mesh coordination function

The mesh coordination function (MCF) is a new coordination function introduced with the IEEE 802.11s specification. The MCF includes both contention-based channel access and collision-free channel access mechanisms. The MCF adopts EDCA as its contention-based mechanism, exactly how it is used in HCF, as previously presented. The collision-free mechanism, called MCF controlled channel access (MCCA), is proposed to optimize the frame exchanges in the mesh basic service set (MBSS), by guaranteeing channel access opportunities for QoS-aware traffic.

The MCCA is an optional MAC mechanism, which operates alongside with EDCA on channel access control. MCCA-enabled mesh STAs can reserve the channel for prioritized access during predefined intervals, called MCCA opportunities (MCCAOPs). A reservation specifies a regular schedule of MCCAOPs in the delivery traffic indication message (DTIM) interval. The DTIM interval is the period between two beacon frames containing traffic indication messages. The interval between consecutive DTIM beacon frames is divided into slots of 32 µs. The schedule is set up between a mesh STA that initiates the reservation (MCCAOP owner) and one or more mesh stations (MCCAOP responders).

To set-up a reservation, an MCCA setup request is transmitted by the MCCAOP owner to the intended MCCAOP responder(s). The MCCAOP responders upon receipt of an MCCA setup request check the requested reservation for any conflicting MCCAOP and transmits an MCCA setup reply accepting or rejecting it. These frame exchanges are performed through management frames of type action with information elements encapsulated in the payload.

An MCCA setup request contains three reservation parameters: *offset*, *duration*, and *periodicity*. The maximum duration of an MCCAOP is 4096 µs, which means 128 slots of 32 µs each. The *periodicity* value defines the number of MCCAOPs arranged in the DTIM interval, and the *offset* value indicates the beginning of the first MCCAOP in each DTIM interval (see Figure 2.9).

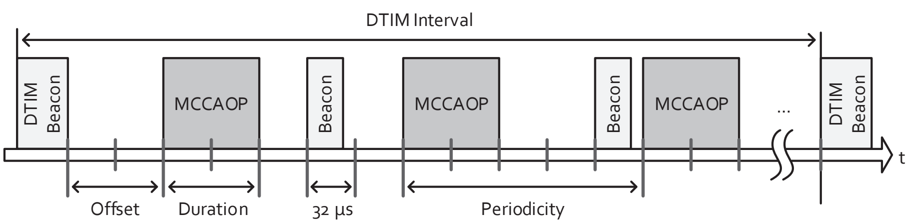

Figure 2.9 Example of an MCCAOP reservation.[h]

To reduce the probability of conflicting reservations, the MCCAOP owner and the MCCAOP responders periodically advertise their MCCAOP reservations to their neighbors via an MCCAOP advertisement (MADV) frame. This MADV frame consists of transmitter (Tx)–receiver (Rx), broadcast, and interference (IR) periods report. The Tx-Rx periods report includes all individually addressed MCCAOPs in which a mesh STA is involved, either as an owner or as a responder. Broadcast periods report includes all group addressed MCCAOPs in which a mesh STA is involved, and also may include known beacon transmission times. The IR periods report includes the periods during which a mesh STA is neither an owner nor a responder, but are reported as busy by its neighbors' Tx-Rx/IR periods report. IR periods are directly derived from the Tx-Rx and the broadcast periods reports of MADV frames transmitted by the mesh STAs in the neighborhood. This way, mesh STAs are able to track MCCAOPs reservations and avoid reservation conflicts.

Moreover, the MADV frame also includes the MCCA access fraction (MAF), which is a ratio of the time reserved for MCCAOPs in the DTIM interval. The MAF is upper bounded by MAF limit value, which defines the maximum ratio of DTIM interval usage. This MAF limit is known by all MCCA-enabled mesh STAs, and cannot be exceeded, in order to allow the mesh STAs to access the channel through normal EDCA operation during the DTIM interval. This MAF limit prevents an excessive channel occupation by MCCAOPs.

Upon the reservation establishment, the MCCAOP owner needs to contend for the channel during the MCCAOP using the EDCA scheme. Only after successfully obtaining an EDCA-TXOP, the MCCAOP owner can initiate its frames transmission. At the beginning of the MCCAOP, when contending for an EDCA-TXOP, the MCCAOP owner experiences no competition from other MCCA-enabled STAs in the neighborhood, since its EDCAF parameters for all ACs are replaced by the minimum contention values, which are AIFSN = 1 (i.e. AIFS = PIFS), $aCW_{min} = 0$, and $aCW_{max} = 31$. In addition, data frames retransmission is disabled during the MCCAOP.

During the MCCAOP, MCCA-enabled mesh STAs that are in the neighborhood of MCCAOP owner and/or MCCAOP responders maintain a resource allocation vector (RAV) to indicate busy channel for the duration of the MCCAOP. RAV contains an index of future MCCAOPs based on the information available in the IR periods report. To increase the reservation protection, MCCA-enabled mesh STAs set their network allocation vector (NAV) at the first frame exchange sequence in the MCCAOP. If RAV or NAV are active, MCCA-enabled mesh STAs cannot contend for the channel access. Moreover, EDCA-TXOPs of MCCA-enabled mesh STAs are not allowed to extend across any of their tracked MCCAOP reservations.

To understand how the channel access is performed during an MCCAOP reservation, Figure 2.10 illustrates an example, in which there are four mesh STAs (A, B, C and D) in the transmission range of each other. Mesh STAs A, B, C are MCCA-enabled stations, whereas mesh STA D is a non-MCCA station. The mesh STA B, which is the MCCAOP owner, willing to transmit data frames to mesh STA C during the MCCAOP reservation, must contend for the channel access, i.e., the mesh STA B must sense the channel idle for an AIFS period, and then start the backoff process. The mesh STA B can only transmit during its MCCAOP when gaining the channel access by obtaining an EDCA-TXOP (i.e. when its backoff counter reaches zero). Moreover, mesh STA A, which is an MCCA-enabled neighbor of mesh STA B, in order to protect the channel access during MCCAOP, must set its RAV at the beginning of the MCCAOP. The RAV is set based on the IR period report previously exchanged by the MCCAOP-enabled stations. Furthermore, upon the first data frame transmission from mesh STA B to mesh STA C, both mesh STAs A and D must set their NAV according to the MCCAOP remaining duration.

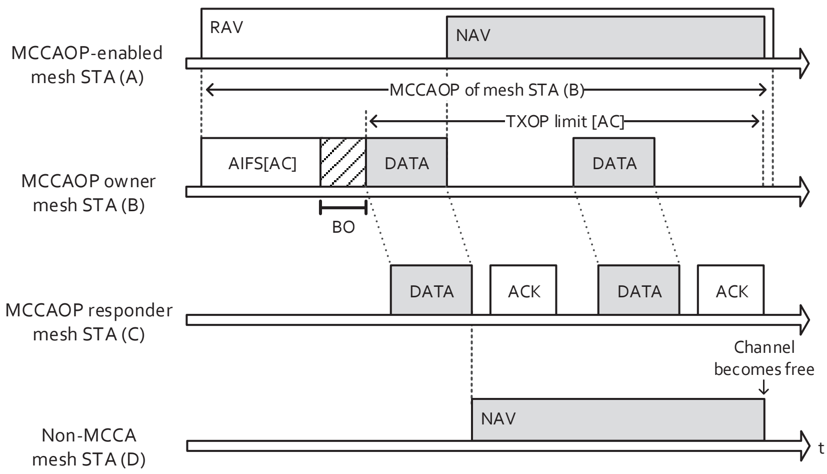

Figure 2.10 Example of channel access during an MCCAOP reservation.[i]

2.4 Summary

This chapter presented an overview of the specification of the IEEE 802.11s wireless mesh standard. A description of mesh elements and characteristics has been provided, focusing in mesh establishment, frame addressing, path selection and link management. Moreover, an overview of the PHY layer specification of IEEE 802.11 family of standards has been provided, where a chronological description of the evolution of the standards has been presented. Finally, the medium access control (MAC) schemes defined by the IEEE 802.11s standard have been presented, emphasizing aspects related to the quality of service (QoS) provisioning. The EDCA mechanism is the default MAC scheme defined for the IEEE 802.11s WMN standard, where channel access categories are defined for service differentiation, and the MCCA mechanism is proposed as an optional MAC scheme, which introduces prioritized channel access during reserved periods.

CHAPTER 3

Real-time communication support in IEEE 802.11-based wireless mesh networks

This chapter discusses some aspects related to the real-time (RT) communication support in 802.11-based wireless mesh networks, and reviews relevant work on quality of service (QoS) provisioning. This chapter is largely drawn from the following published book chapter:

C. M. D. Viegas, F. Vasques, P. Portugal. Real-Time Communication Support in IEEE 802.11-based Wireless Mesh Networks. In M. Khosrow-Pour (Ed.), *Encyclopedia of Information Science and Technology*, ch. 713, pp. 7247–7259. IGI Global, Hershey, PA, USA, 3rd ed., 2014. `http://dx.doi.org/10.4018/978-1-4666-5888-2.ch713`

3.1 Introduction

The IEEE 802.11 family of wireless standards became the dominant solution for wireless local area networks (WLANs) due to its performance, low cost and fast deployment characteristics [76, 77]. Along its increasing popularity, there was a demand for interconnection of several different devices in the network, sharing common services. Thus, wireless mesh networks (WMNs) appeared as a promising approach to deal with heterogeneity and diversity of those wireless networks [78].

WMNs provide greater flexibility, reliability and performance when compared to traditional wireless networks [79], since they are able to extend the network coverage without any additional infrastructure by using multi-hop communication, where nodes can relay traffic by traversing multiple hops to reach a destination [8].

There are several application domains where WMNs can be applied, such as home and enterprise networks, transportation and real-time systems, building automation and metropolitan area networks [9]. However, despite the several application domains, in this chapter we are particularly interested in studying the support of real-time applications in WMNs.

Real-time applications are usually not resilient to delay and jitter constraints. The deployment of real-time services over WMNs requires the support of quality of service (QoS). To guarantee time-constrained communication in wireless multi-hop networks, real-time communication must be established according to specific traffic characteristics and QoS requirements.

Despite the benefits of WMNs, the main challenging task concerning QoS provisioning in WMNs is the communication channel that is a shared resource in a multi-hop relaying infrastructure. Also, it is important to consider some characteristics inherent to wireless mesh environments such as link instability, lack of central infrastructure, nodes mobility, channel access contention and hidden terminal problem [78].

This chapter discusses the aforementioned challenges related to QoS provisioning, targeting real-time communication support in IEEE 802.11 WMNs at medium access control (MAC) sub-layer. A literature review of available techniques on the referred topic will be presented and discussed.

3.2 Real-time communication support

To support real-time communication in multi-hop networks it is necessary to ensure network is properly dimensioned and enough resources are reserved in order to maintain QoS guarantees. For QoS provisioning, it may be required the reservation in advance of some resources, as the adequate reservations will help by maintaining delay, jitter and negotiated upper bound for packet loss rate requirements [25].

The internet engineering task force (IETF) developed the integrated services (IntServ) and differentiated services (DiffServ) techniques aiming QoS provisioning in IP-based networks [26, 80]. The IntServ technique aims to provide per-flow QoS guarantees to individual applications, where several services classes are defined. Those applications should be able to select a class based on their QoS requirements. It uses resource reservation protocol (RSVP) to allocate resources to links along a data path. However, IntServ scheme has scalability problems, where maintaining a large number of flows requires enormous amount of resources [25].

DiffServ consists of the specification of a restricted communication domain with specific requirements, delimited by boundary routers that control the ingress and egress of network traffic. Ingress boundary routers are required to classify traffic according to a service level specification. DiffServ has a traffic conditioner, in which are included the traffic characteristics and the performance metrics (delay, throughput, etc.). At internal nodes, the traffic is processed at maximum available speed, once traffic classification has been previously done by boundary routers [25, 81].

However, when considering the mobility of wireless mesh networks, neither IntServ nor DiffServ techniques are able to adequately deal with mobile nodes. This weakness is due to difficulties in reserving resources for mobile environments. As IntServ works with RSVP allocating resources to the links along data paths, with nodes mobility a path will change and consequently there will be no reserved resources in a future router where the mobile node may connect. Likewise, the main issue of DiffServ is the service level specification, i.e. when a mobile node moves to a new network and it tries to establish a new specification, the resources must be available in that network to support the required QoS. If there are not enough available resources, the mobile node could face degraded QoS provisioning [25].

In this context, additional mechanisms must be devised to achieve QoS in wireless mesh networks. In the following subsections, we survey the techniques available in the literature that can be used for QoS provisioning, such as admission control and resource reservation, congestion control, rate adaptation, multi-channel and channel assignment.

3.2.1 Admission control and resource reservation

Admission control is one of the key traffic-management mechanisms that must be deployed for QoS provisioning [82]. This technique consists in admitting traffic flows according to some available resources, such as bandwidth, time-slots, channels, and also according to some requirements, as throughput, delay and jitter constraints. A traffic flow is only admitted in the network if there are available resources and QoS requirements can be met. The admission control technique is the premise for the implementation of QoS provisioning techniques.

As network resources are required for QoS provisioning, resource reservation techniques consist in ensuring that real-time traffic obtains sufficient bandwidth and/or time-slots throughout their transmission time, in order to satisfy their QoS requirements. The bandwidth reservation can be achieved by assigning more channel access opportunities or directly allocating exclusive bandwidth for QoS-dependent sessions [18].

In the literature, there is a lot of research on resource reservation proposals to support real-time communication in multi-hop networks. These proposals aim to improve the IEEE 802.11 MAC mechanisms and to mitigate their impairments. Usually, resource reservation techniques are combined with admission control mechanisms in order to improve capacity and maximize throughput in WMNs.

Yang et al. [58] propose the admission control based on active neighbor bandwidth reservation (AC-ANBR), a bandwidth reservation scheme that admits real-time traffic by guaranteeing QoS of all existing flows based on active neighbor bandwidth. It estimates the available bandwidth of each node and the required bandwidth of each new flow (by overhearing surrounding transmissions), and this way avoids the real-time traffic from overusing available bandwidth resources.

Toscano & Lo Bello [83] propose a bandwidth-efficient admission control mechanism for wireless industrial communication where the messages transmission is ruled by an earliest deadline first (EDF) scheduler. This mechanism associates a target success rate for each real-time flow, which is the minimum fraction of messages that must be correctly delivered and on time (without missing deadlines). It calculates the feasibility of a flow by taking into account the message loss and retransmissions according to known statistics of wireless links. Both transmissions and retransmissions are scheduled according to a non-preemptive EDF algorithm and the admission control mechanism considers the loss rate and the desired success rate.

BOR/AC is a bandwidth-aware opportunistic routing protocol with admission control to provide bandwidth assurance for traffic flows [59]. It takes into account the expected transmission cost and the expected available bandwidth of each node based on the probabilities of link delivery, forwarding candidates and nodes prioritization policy. If the expected available bandwidth under opportunistic routing is greater than the bandwidth requirement of a traffic flow, the traffic will be admitted and forwarded to the destination. Nodes with higher available bandwidth and lower transmission cost are selected as forwarders in order to provide a good trade-off between the available bandwidth and transmission cost.

Regarding the resource reservation techniques, Ould Cheikh & Gueroui [53] proposed a bandwidth reservation scheme, called multi-hop bandwidth reservation in WMN (MBRWMN). It computes a new metric weighted airtime metric (WAM) based on the available and the required bandwidth estimation in order to determine the best path between source and destination.

Carlson et al. [52] propose the distributed end-to-end allocation of time slots for real-time (DARE) protocol as a scheme to perform end-to-end reservations for real-time traffic. It operates at MAC sub-layer by reserving periodically time slots in all nodes along a path. This protocol extends the concept of request to send (RTS) and clear to send (CTS) messages and it introduces the request to reserve (RTR) and clear to reserve (CTR) messages to perform reservations. DARE offers a reliable and efficient support for QoS applications by providing constant throughput and low and stable end-to-end delay for a reserved real-time flow.

A common technique to reserve resources in a network is to broadcast the QoS requirements of stations in the WMN. In this sense, the EDCA with resource reservation (EDCA/RR) was proposed to improve EDCA by allowing resource reservation aiming real-time guarantees [48]. It extends EDCA by offering its existing functionalities and it adds distributed resource reservation, admission control and scheduling schemes. To perform a reservation, the stations must broadcast requests and their QoS requirements must be known by the routing protocol. Resources are only reserved to the high priority traffic, whereas low priority traffic is processed according to EDCA's admission control. As a disadvantage of EDCA/RR, the routing protocol must know in advance all the QoS requirements which is not always feasible.

When considering MAC sub-layer of IEEE 802.11s WMNs, novel proposals were proposed aiming to mitigate the MCCA impairments. Krasilov et al. [43] have shown that MCCA suffers from external interferences once non-MCCA mesh stations are not aware of MCCA opportunity (MCCAOP) reservations. The authors proposed an improved resource allocation vector (RAV) setup called directional RAV (DRAV) in order to avoid the problem of ACK-induced interference, which consists of collision of an ACK frame with a MCCAOP. DRAV scheme forbids a mesh station to start an EDCA-TXOP if it crosses any MCCAOP reservation. The results have shown that all established flows were transmitted with acceptable quality. However, the background traffic was neglected and this is unrealistic when considering WMNs.

An alternative approach to reserve time slots for collision-free data transmission is proposed as medium access through reservation (MARE) [84]. This scheme, instead of using the excessive beaconing broadcast employed by MCCA, it uses a RTS/CTS-based mechanism with the introduction of control frames to notify neighborhood about reservations. The proposed scheme is able to reduce the network overhead since it reduces the collision probability, when compared to the MCCA. However, all mesh stations are required to keep track of the available slots by storing information related to all active reservations, which may not be feasible depending on the number of mesh stations in the network.

Ali et al. [85] proposed another enhancement to MCCA, called enhanced mesh deterministic access (EMDA)[j]. It specifies a scheduler that reserves dimensioned and contiguous MCCAOPs for each mesh station rather than for each flow. This scheme allows an overhead reduction and it balances the voice capacity in the overall network regardless the number of hops traversed. However, this mechanism may prevent non-MCCA mesh stations to transmit at scheduled times since they are postponed to being transmitted after contiguous MCCAOPs. If multiple MCCAOPs are contiguously reserved, the non-MCCA mesh stations can experience unpredictable delays or even being prevented from transmitting.

Although the combination of admission control and resource reservation mechanisms seem reasonable to provide QoS, in case of any congestion in the network, the communication performance may be degraded and the real-time traffic may present an unpredictable behavior. This way, congestion control techniques should be applied in order to improve QoS provisioning in addition to these techniques.

3.2.2 Congestion control

Frequent transmission failures over the wireless channel, due to its non-deterministic behavior, its error-prone nature and surrounding interferences [60], require an efficient congestion control mechanism in order to reduce interferences and guarantee a fair channel usage among mesh stations.

According to [86], the IEEE 802.11s standard defines an optional hop-by-hop congestion control mechanism in which each mesh station observes the congestion level based on the incoming and outgoing traffic. When the network traffic is increased to a point that a mesh station is unable to forward and source data upstream as fast as the incoming rate, a congestion occurs. The mesh station must notify its one-hop neighbors. Then, the neighbors limit the rate at which they are sending to the congested mesh station.

Chen & Xu [87] proposed a random routing algorithm based on path weight in order to prevent congestion control. The algorithm assigns a weight for each path and then randomly selects one of them according to the weights. If a weight is higher, then the probability of a path from being selected is greater. It takes into account the distance vector and the load of gateway nodes to select the most favorable gateway for data relaying. This method can distribute the traffic to different paths and balance the network load.

Choi et al. [88] propose a congestion control scheme which applies adaptive modulation and coding scheme and effective buffer usage. It uses multiple fragmentation thresholds, modulation levels and coding rates for different data rates, and effective buffer usage. If the buffer of a downstream mesh station does not exceed a threshold, the upstream mesh station transmits fragmented data units based on the received channel state information. Otherwise, if the buffer exceeds a threshold, the upstream mesh station transmits fragmented data units by considering the received channel state information and also the downstream mesh station channel condition, for congestion control. This way, channel state information can be effectively used to increase the network throughput.

3.2.3 Rate adaptation

The rate adaptation technique consists of a mechanism that uses multi-rate capability of the network in order to adapt the transmission data rate according to channel conditions. Multi-rate capability can exploit the short inter-nodes distance in high-density networks owing the chance to use higher rates considering the rate-distance trade-off. According to [89], in the IEEE 802.11 PHY layer there is a trade-off between the transmission rate and distance, where the higher rates suffer from shorter transmission range, while throughput-limited lower rates show longer transmission range. This is the reason why rate adaptation technique is needed to overcome the rate-distance trade-off. The effectiveness of a rate adaptation scheme depends on how fast it can respond to the variation of wireless channel conditions.

In the literature there are two well-known IEEE 802.11 rate adaptation schemes, namely automatic rate fallback (ARF) and receiver-based auto rate (RBAR) [89–91].

ARF is an open-loop rate adaptation scheme, where transmitter makes the rate adaptation decision based only on its local ACK information, without requiring any additional interaction between transmitter and receiver. ARF alternates transmission rates by keeping track of a timing function and missing ACK frames, i.e. if transmitter does not correctly receive two consecutive ACK frames, subsequent data frames are transmitted at lower rate and a timer is started. When this timer expires or the number of successfully received ACKs reaches 10, the transmission rate is set to the higher rate and the timer is restarted. However, when the rate is increased, the first transmission must be successful, otherwise the rate is immediately decreased again.

ARF scheme has some drawbacks, as it increases and decreases the transmission rate based on ACK reception without considering the cause of the transmission failure, making the scheme slower when channel condition fluctuates. Also, if the channel condition remains unstable, every 10 successfully transmitted packets it will try to use higher rates, by this way decreasing the throughput.

RBAR is a closed-loop rate adaptation scheme, where receiver specifies the best transmission rate and sends it back to transmitter, which uses it to transmit data. The RBAR exchanges RTS/CTS frames between source and destination in order to start a transmission. The receiver of RTS frame calculates the transmission rate based on measured the signal-to-noise ratio (SNR) of received RTS. Then, the calculated rate is sent to the transmitter through CTS frame. RTS, CTS and data frames are modified to contain the information about the data transmission size and rate to allow all nodes within the transmission range to correctly set their network allocation vector (NAV).

RBAR has some limitations, since it may not work properly if channels change faster that SNR for the RTS frame is different than for the packet. Also, it assumes that SNR of a given packet is available at receiver, which is not always true as some IEEE 802.11 devices provide a SNR estimation.

Lacage et al. [90] propose the adaptive ARF (AARF) as a modification of ARF. As one of the ARF drawbacks is the decreasing throughput by the usage of higher rates every 10 successfully transmitted packets, AARF adapts this threshold continuously at runtime to better reflect channel conditions, by using binary exponential backoff (BEB). Basically, when the transmission fails, the lower rate is immediately switched back (as in ARF), but the number of consecutive successful transmissions required to switch to a higher rate is doubled (until a maximum of 50). When the rate is decreased due to two consecutive failed transmissions, this threshold is restored to the initial value of 10. This threshold adaptation increases the period between successive failed attempts to use higher rates, being able to maximize the throughput due to less failed transmissions and retransmissions.

Vitturi et al. [92] propose two rate adaptation approaches based on ARF, static retransmission rate ARF (SARF) and fast rate reduction ARF (FARF). Both behave like ARF, where SARF selects the lowest data rate at each packet retransmission in order to limit the number of ARF transmission attempts, providing the highest success probability. After two consecutive failed transmissions at rate r_i interleaved by a successful retransmission at lowest data rate, SARF selects the rate r_{i-1} for the next packet transmission. On the other side, in case of transmission failure FARF immediately selects the lowest data rate (instead of waiting for two ACK misses as in ARF) for the next packet transmissions.

Multi-hop transmission opportunity (MTOP) was proposed as a multi-rate adaptation mechanism that allows a frame to be forwarded a number of hops consecutively without contending for the wireless medium [93]. This mechanism is applied to multi-hop networks and it takes advantage of different defer thresholds (multi-rate transmissions) to send frames to the next hops. Basically, MTOP works after a TXOP when it cannot allow frames to be transmitted in the given opportunity. By transmitting at different rates (1 Mbps and 11 Mbps, for example), it requires different defer thresholds (-105.1 dBm and -96.2 dBm, respectively). The difference between these defer thresholds is 8.9 dB and this is the multi-rate margin that MTOP exploits by allowing a frame to travel 1 or 2 more hops with a single medium access. This technique opens several interesting directions of research, as it can be employed in multi-radio/multi-channel networks.

3.2.4 Multi-channel communication and channel assignment

The multi-channel technique consists in exploiting multiple channels available in the wireless domain to transmit different frame types. In general, it consists in separate/reserve a channel to transmit control frames (common control channel) and the remaining channels to transmit data frames (data channels). The objective of this technique is to increase the overall network throughput, reduce the number of collisions and decrease the transmission delays.

Fast forward medium access control (FFMAC) protocol is a multi-channel technique proposed to WMNs [24]. It provides real-time guarantees through multiple communication channels, defining a multi-hop path (through IEEE 802.11s hybrid wireless mesh protocol (HWMP) routing protocol). It reserves one channel to exchange control frames (control channel) and the remainder channels to exchange data frames (data channels). The frames exchange between a source and a destination node in a multi-hop environment is performed by the following forwarding model: the source broadcasts a route request (RREQ) frame on the control channel to its neighbors and they rebroadcast to neighbors until it reaches the destination. Then, the destination answers with a route reply (RREP) frame that is broadcast by neighbors until it reaches the source. This way, a transmission path is established for transmissions between the source and the destination nodes. After the path establishment, the source node sends a data frame and waits for an ACK from the neighbor node. However, the neighbor node sends an ACK to the source and also to the next neighbor to reserve the medium. If next neighbor answers with a CTS frame, the data is finally forwarded and acknowledged again. And thus, it is repeated through neighbors until the frame reaches destination. The simulation results indicate that this forwarding technique is able to reduce end-to-end delay and to increase network throughput.

Another channel reservation technique is the AODV-multi radio with channel reservation (AODV-MRCR) [94]. It is a multi-radio on demand routing protocol that reserves a list of channels for the common traffic in WMNs. The AODV-MRCR tries to use the multi-links available among neighbors by reserving one link for common traffic and the remaining links for other traffic types. It is implemented by using ad hoc on-demand distance vector (AODV) routing discovery to distribute a channel reservation list for all nodes along a path. According to the authors, AODV-MRCR is able to reduce the interference for common traffic and to support full duplex transmission, moreover the simulation results showed that proposed protocol was able to reduce throughput, end-to-end delay and packet loss ratio.

Kyasanur et al. [95] propose two link-layer multi-channel protocols. The multi-channel MAC (MMAC) is designed for single-radio devices only, where stations negotiate channels using control messages in order to distribute the traffic load across the channels. The hybrid multi-channel protocol (HMCP) is designed for multi-radio devices, where some specified channels are assigned (fixed) to some radio interfaces while the remaining channels are available for channel switching with the same objective of traffic load balancing across the channels.

Hoblos & Peyravi [96] presented fair access rate (FAR). It is a multi-hop multi-channel rate adaptation scheme that assigns variable transmission rates to different nodes, based on hop count, aggregated traffic and network topology. FAR assigns variable transmission rates to relay nodes based on their aggregate Erlang-B blocking probabilities. The main idea is to compensate a node distance and its aggregated relay load with its medium access rate.

Across multiple channels, efficient channel selection is essential in mesh networks in order to minimize the contention periods and the interference among co-channels. Thus, the channel assignment technique was proposed in order to mitigate these issues.

The channel assignment technique consists in assigning channels to radio interfaces in order to achieve efficient channel utilization and minimize the interferences [61, 97]. The goal of channel assignment in a multi-channel environment is to bind each network interface to a radio channel in such a way that available bandwidth on each link is proportional to its expected load.

Hyacinth is a channel assignment that builds a spanning tree which is dynamically adapted according to the varying traffic loads [98]. Each node separates a set of interfaces (up-NICs) that will be assigned by hierarchical mesh stations (parents) and another set of interfaces (down-NICs) that will be assigned by the node itself. Each node periodically exchanges its individual channel usage statistics with all neighbors in the interference range. If it finds a less loaded channel, the node changes a down-NIC (that is on heavily-loaded channel) to a less loaded channel and updates the affected other NICs (children) in the spanning tree.

Ghannay & Gammar [99] present the joint routing and channel assignment protocol (JRCAP) as a distributed load aware channel assignment scheme that assigns the channel during the routing process. JRCAP divides the network topology into balanced clusters and allocates a fixed channel to each one. The routing process is on-demand HWMP-inspired, in which a mesh station broadcasts a route request on its interface (the same that was assigned a fixed channel in the cluster) in order to achieve a path to a destination. Upon reception of that route request by another mesh station, a new routing metric, which take into account channel diversity and link capacity, is computed in order to select the best channel to assign as reverse path.

Skalli et al. [97] presented the mesh-based traffic and interference-aware channel-assignment (MesTiC). It is a static centralized channel assignment scheme based on a ranking function that take into account the traffic, the number of hops and the amount of radio interfaces per node. It is a polynomial time greedy algorithm, which visits nodes in the decreasing order of their rank. The rank of each node is computed on the basis of its link traffic characteristics, topological properties and number of radio interfaces. If a node relays more traffic (higher rank), it is reasonable to assign it a channel with less interference in order to increase the network throughput.

Bononi et al. [100] present an architecture that combines a distributed channel allocation, routing and multi-radio multi-channel schemes. Channel assignment and fast MAC architecture (CAFMA) extends IEEE 802.11e EDCA MAC scheme to support multichannel multi-radio technology and also to provide fast data relaying on multi-hop topologies. Path discovery protocol is AODV-inspired with a contention-aware metric which combines hop count and the number of interferers in the control channel. The channel allocation is performed on-demand in coordination with path discovery protocol.

3.3 Future research directions

As seen, the MAC mechanisms of IEEE 802.11 standard do not effectively support real-time communication, since they are not able to impose the traffic differentiation adequately. Regarding the QoS provisioning in multi-hop networks, the communication performance is highly affected by the interferences caused by wireless devices in the vicinity.

In the literature there are several techniques available to support real-time communication in IEEE 802.11-based mesh networks. However, these techniques themselves are not sufficient to guarantee a satisfactory QoS level. In this sense, to improve the real-time communication support in WMNs, a combination of different techniques seems to be a promising approach.

To reduce the surrounding interferences over the real-time communication, a resource reservation scheme should be used to reserve transmission opportunities to the real-time traffic. However, in a resource reservation scheme, the admission control is crucial to protect resources allocated for QoS sessions and to improve the bandwidth usage. Thus, a resource reservation scheme should be combined with an admission control mechanism.

Another common approach in supporting real-time communication is the network utility management through the cross-layer design of resource allocation and admission control mechanisms. The communication performance can be optimized by using a cross-layer design, where multiple layers are involved in the resource allocation and may not be achieved by traditional layering architecture. For example, if a rate control mechanism is proposed without considering the resource reservations at underlying layers, it might not be effective and may degrade the communication performance.

Real-time communication demands continuous network connectivity to guarantee that deadlines will be met. For an efficient real-time support, the wireless mesh networks require mechanisms for the mobility management, where efficient roaming techniques (handoff) are essential to ensure connectivity and uninterrupted service delivery. The handoff is a mobility process which allows a mobile station to move from one access point to another. During the handoff process, there is a period where stations are unable to transmit due to the access point change. This interruption period breaks the concept of connection continuity and should be avoided or reduced. Further research on this topic is important for scenarios where mobile devices take place.

3.4 Conclusion

This chapter presented a study on techniques to support real-time communication at MAC sub-layer of IEEE 802.11-based mesh networks. A survey on QoS provisioning was presented, intended to identify the most relevant work in the area.

As seen, according to the literature review, there are several techniques for QoS provisioning in WMNs. A combination of these techniques is an efficient mean to achieve the purpose of real-time communication support in WMNs. As stated by [82] admission control is the premise to implement other real-time techniques. Moreover, in a resource reservation scheme, admission control is crucial to protect resources allocated for QoS sessions and to improve bandwidth efficiency [18].

According to [101], one common approach in WMN communication performance optimization is network utility management through the cross-layer design of control and resource allocation mechanisms. The network performance optimization can be obtained by cross-layer design, where multiple layers are involved in the resource allocation and may not be achieved by traditional layering architecture. If a rate control mechanism is proposed without considering the resource reservations at underlying layers, it cannot be effective and may degrades the network performance.

In addition, real-time communication can take advantage of multi-channel capacity of IEEE 802.11 and implements the common control channel approach in order to send control frames in one channel (control channel) and the remaining channels to transmit the overall real-time data (data channels). This technique is effective to reduce the end-to-end delay and to increase throughput, as reported in [24, 94].

The effective channel usage is also crucial for communication performance. However, when the network is highly congested, none of these schemes can prevent QoS degradation. This way, an intra-mesh congestion control and rate adaptation techniques can take place.

CHAPTER 4

Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources

This chapter presents a performance assessment of the enhanced distributed channel access (EDCA) MAC mechanism regarding the support of real-time (RT) communication in 802.11s wireless mesh networks (WMNs), when the wireless channel is shared with uncontrolled non-RT traffic sources. A set of simulations experiments were defined, and several communication scenarios with different interference loads were assessed. In addition, a sensitivity analysis of the network configuration parameters is presented, in order to provide useful hints on setting the channel contention and routing parameter values. This chapter is a reproduction of the contents of the following published paper:

C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources. *EURASIP Journal on Wireless Communications and Networking*, 2014(219):1–15, 2014. `http://dx.doi.org/10.1186/1687-1499-2014-219`

Abstract

With the widespread deployment of wireless mesh networks (WMNs) in industrial environments, real-time (RT) communication may benefit from the multi-hop relaying infrastructure provided by WMNs. However, RT communication must be able to coexist with non-RT traffic sources that will interfere with RT communication. Within this context, this chapter assesses the impact of interferences caused by non-RT traffic sources upon RT traffic in IEEE 802.11s mesh networks. Through an extensive set of simulations, we assess the impact

of external traffic sources upon a set of RT message streams in different communication scenarios. According to the simulation results, we infer that RT traffic in 802.11s networks may be highly affected by external interferences, and therefore, such interferences must be taken into account when setting-up 802.11s networks. By varying the network load imposed by external interferences, we provide some useful hints about utilization thresholds above which the network can no longer reliably support RT traffic. We also present insights about the setting-up of some network parameters in order to optimize the RT communication performance.

4.1 Introduction

The IEEE 802.11 family of wireless protocols became the dominant solution for wireless local area networks (WLANs) due to its high performance, low cost, and fast deployment characteristics [77]. Along its increasing popularity, there was also a demand for sharing common services among different devices connected to the network. Wireless mesh networks (WMNs) appeared as a promising approach to deal with heterogeneity and diversity of wireless networks, by introducing multi-hop forwarding at medium access control (MAC) level and allowing wireless interconnection of multiple access points [10].

WMNs provide greater flexibility, reliability, and performance when compared to traditional wireless networks, since they are able to extend network coverage without any additional infrastructure by using multi-hop communication, where nodes can relay traffic by traversing multiple hops to reach a destination [10].

Packet forwarding in WMNs may be implemented at layer 3 or layer 2. In the former, which is the most common WMN implementation, packet forwarding is performed at network layer by means of internet protocol (IP). In the latter, frame forwarding is performed at data link layer, being the MAC addresses used to deliver frames through the WMN backbone [102]. The IEEE 802.11s standard specifies a layer 2 WMN aiming to extend the coverage of traditional 802.11 WLANs and to allow the support of a larger diversity of wireless technologies [11].

There are several application domains where WMNs can be applied, such as home and enterprise networks, transportation and real-time (RT) systems, and building automation and metropolitan area networks [9]. In this chapter, we are particularly interested in the support of RT applications using WMNs.

RT applications are usually not resilient to delay and jitter constraints. Therefore, the deployment of RT services over WMNs requires the use of quality of service (QoS) mechanisms. Most of current RT applications require a priori reservation of network resources (e.g., link bandwidth, time slots, and channels) in order to meet QoS requirements. Within this context, several recent research efforts targeted RT communication support and resource reservation techniques over multi-hop networks [43, 49, 51, 52, 54, 58, 103–105].

Most part of the proposed resource reservation techniques are focused on the RT traffic itself, regardless of the interference of non-RT traffic sources. Usually, authors focus on the proposed mechanisms and their performance, and, in some cases, relevant simplifications are made (e.g., ideal wireless channel conditions [106]). Consequently, the related assessments may not reflect the real-world behavior, which is usually prone to interference of non-RT traffic sources that may impact in the communication performance, as highlighted in [40, 107, 108].

Within this context, the main goal of this work is to provide a useful insight upon the impact of interfering traffic over RT communication in single-channel IEEE 802.11s networks. To do so, a simulation assessment was carried out using network simulator 3 (ns-3) and considering real-world scenarios. Non-RT traffic flows from different sources were injected in the network in order to evaluate their impact over RT communication performance. This evaluation indicates that resource reservation techniques must consider the impact of the external traffic interference in order to maintain response times of RT traffic under acceptable thresholds. Otherwise, the communication services may not be able to fulfill the expected RT requirements of the supported applications.

This work extends a performance assessment previously presented in [40]. Such work evaluated the communication performance under periodic interference in a mesh-based network. This work introduces a new realistic interference model, with aperiodic and bursty traffic, in a 802.11s WMN. Therefore, more realistic communication scenarios have been considered.

The remainder of this chapter is organized as follows. Section 4.2 presents an overview of IEEE 802.11s standard by describing its main functionalities. Section 4.3 presents some related work on MAC performance analysis and resource reservation techniques. Section 4.4 formulates the problem to be evaluated in this chapter. Section 4.5 describes the simulation scenarios used for this evaluation. Section 4.6 presents an analysis of the results. Finally, Section 4.7 concludes the chapter.

4.2 IEEE 802.11s overview

As an amendment to the IEEE 802.11 standard, the IEEE 802.11s WMN standard uses the same physical (PHY) layer specification and MAC sublayer architecture, with additional extensions [11]. It introduces forwarding at MAC level that uses a multi-hop wireless relaying infrastructure, where nodes cooperatively maintain the network connectivity. Every node can work as a relaying node, forwarding frames in behalf of its neighbor nodes. The mesh connectivity is managed by the mesh peering management (MPM) protocol, which is responsible to establish, manage, and tear down mesh peer links among mesh stations (STAs).

The default path selection protocol is the hybrid wireless mesh protocol (HWMP), which combines reactive (on-demand) path selection with extensions to enable proactive (tree-based) path selection. The reactive mode is based on the *ad hoc* on-demand distance vector (AODV) routing protocol, which allows mesh STAs to communicate in a peer-to-peer basis [109]. In the proactive mode, additional tree building functionality is added to the on-demand mode, by configuring a mesh STA as root of a path tree (formally root mesh STA). The root is responsible to coordinate the path selection by periodically sending proactive information elements to the mesh STAs.

HWMP uses radio-aware metrics, being the airtime link metric the default one. The airtime link metric is proposed for basic interoperability among 802.11s devices and reflects the amount of channel resources consumed during a frame transmission over a particular link. The path with smallest airtime link metric is considered to be the best forwarding path [66].

The medium access control is managed by the mesh coordination function (MCF), which schedules the access to the channel by allocating transmission opportunities (TXOPs) to mesh STAs. A TXOP is a time-bounded interval in which a station keeps the medium access control [107]. MCF adopts the enhanced distributed channel access (EDCA) as the mandatory MAC scheme, which is a contention-based channel access mechanism based on carrier sensing multiple access with collision avoidance (CSMA/CA).

EDCA provides service differentiation by classifying frames from upper layers in different access categories (ACs). There are four defined ACs, in which frames of different traffic types are mapped according to the application and its QoS requirements. These ACs are based on eight priority levels of IEEE 802.1D standard, as follows [15]: background (BK), best effort (BE), video (VI), and voice (VO) traffic.

For each AC, an enhanced variant of the distribution coordination function (DCF), called EDCA function (EDCAF), contends for TXOPs using a set of EDCA parameters. These EDCA parameters modify the backoff process with individual interframe spaces and contention windows (CWs) per AC (see Table 4.1).

Table 4.1 Default DCF and EDCA parameter set.

Parameters	**AC**	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	**AIFSN**	**DIFS**
DCF	—	aCW_{min}	aCW_{max}	—	2
EDCA	AC_BK	aCW_{min}	aCW_{max}	7	—
	AC_BE	aCW_{min}	aCW_{max}	3	—
	AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}	2	—
	AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2	—

The values of aCW_{min} and aCW_{max}, which are the minimum and maximum size of CW, respectively, are defined according to the physical standard in use. For IEEE 802.11a/g/n standards, these values are respectively 15 and 1,023 and for IEEE 802.11b are 31 and 1,023. Whenever in the presence of IEEE 802.11b devices, the IEEE 802.11g standard defines 31 and

1,023 values for aCW_{min} and aCW_{max}, respectively, in order to maintain the compatibility between standards [11].

During the contention phase, each station senses the medium in order to start the frame transmission. If the medium is idle for at least one arbitration interframe space (AIFS[AC]), the station transmits its frames. Otherwise, the station initiates a backoff interval in order to avoid collisions. The duration of AIFS[AC] is given by:

$$\mathrm{AIFS[AC]} = \mathrm{AIFSN[AC]} \times \mathrm{aSlotTime} + \mathrm{aSIFSTime}, \tag{4.1}$$

where AIFSN[AC] defines the number of slot times per AC (AIFSN[AC] ≥ 2), aSlotTime is the slot duration and aSIFSTime is the short interframe space (SIFS) duration.

The backoff time is a uniformly distributed value between zero and the size of CW. At each unsuccessful transmission, the size of CW is exponentially increased until it reaches the maximum CW size (aCW_{max}). The CW size is given by:

$$\mathrm{CW[AC]} = \min\Big(2 \times \mathrm{aCW_{min}[AC]} + 1, \mathrm{aCW_{max}[AC]}\Big). \tag{4.2}$$

Once a station has started its backoff time, CW is decremented every slot time. If the medium becomes busy during the backoff, the station pauses the countdown procedure, which will be resumed only when the medium becomes idle again during an AIFS[AC]. The station will only be able to transmit data when its backoff time reaches zero.

If the backoff time of two or more ACs in the same station reaches simultaneously zero, a virtual collision will occur. In this case, the AC with the higher priority will transmit, whereas all other ACs will act as if a collision occurred in the medium.

In addition, there is a request to send/clear to send (RTS/CTS) scheme to solve the hidden terminal problem. This problem occurs when a station is able to receive the signal from two different neighbors, but those neighbors cannot detect the signal from each other. This is an optional mechanism that operates by exchanging RTS and CTS control frames. When a transmitter needs to send its data, it requests the medium usage by sending a RTS frame and waits for a response from the receiver in form of a CTS frame, informing idle medium. If a CTS frame is not received after a RTS, the transmitter starts a backoff time before retransmitting the RTS frame.

The MCF also defines an optional MAC scheme called MCF controlled channel access (MCCA) [11]. It is a collision-free and guaranteed channel access for QoS-aware traffic during reserved periods. MCCA allows mesh STAs to access the channel during predefined intervals with lower contention parameters. It operates alongside EDCA, where a mesh STA obtains a MCCA-TXOP instead of a EDCA-TXOP. Nevertheless, the focus of this chapter is upon WMNs that use the EDCA scheme, which is the mandatory MAC for IEEE 802.11s WMNs.

4.3 Related work

The EDCA mechanism was originally proposed in the IEEE 802.11e standard to reduce the number of occurring collisions at MAC sublayer. Its underlying idea was previously proposed by Deng and Chang in [110]. A set of priority classes are defined, where the higher priority class uses the window $[0, 2^{j+1} - 1]$ and the lower priority class uses the window $[2^{j+1}, 2^{j+2} - 1]$, where j is the backoff stage. As the EDCA mechanism provides four access categories for traffic differentiation, it would be expected that the highest access category (voice) would be adequate to transfer RT traffic. However, some research papers, analyzing single-hop networks, show that default parameter values of EDCA mechanism are just able to guarantee RT requirements for a smaller number of stations with large message stream periods [107].

In analyzing research papers, there are several analytical models that evaluate the EDCA mechanism in single-hop networks [29–34]. However, the majority of these models assume simplified approaches. Common examples of these simplifications are related to the modeling of the AIFS procedure, backoff counter, TXOP, virtual collisions, and retransmission limits. Besides, most of the analytical models presented in the literature assume that the network operates in saturated traffic conditions.

There is also a number of proposals aiming to improve the EDCA mechanism. The assessment presented in [107] shows that EDCA contention parameters play an important role in the communication, where by adjusting them, it is possible to improve the communication performance. In [35], the authors propose to not double the contention window size in the case of a virtual collision that is not followed by a real collision, where the backoff time is shortened and the traffic is only penalized if it collides during the medium access (i.e., a real collision). In [36], contention parameters can be adapted based on the transmission success ratio aiming to reduce the backoff time. If the success ratio is higher, shorter values for CW, AIFS, and TXOP are used. On the contrary, if the success ratio worsens, the contention parameter values are reverted to their default values. In [37], it is proposed a new scheme to adjust the contention window size based on the queue occupancy. If the queue occupancy is greater than a threshold, the CW size is increased by a determined factor.

Concerning the coexistence of EDCA and DCF mechanisms in single-hop networks, the main results show that EDCA mechanism with AIFSN = 2 (default value defined to the voice access category) presents better performance over DCF stations specially for high priority traffic [73, 111]. This specific behavior is a consequence of the different slot decrementing mechanism when compared to the DCF access method.

There is also a set of papers assessing the EDCA scheme in multi-hop networks, where it presents a poor performance due to throughput degradation as the number of hops increases and also due to the hidden terminal problem, which increases the collision probability [112, 113]. In addition, as presented in [114, 115], RTS/CTS mechanism does not improve the network communication performance when considering an *ad hoc*/mesh network. Likewise, in [116], it is shown that RTS/CTS mechanism only increases the network overhead.

Despite the MCF scheme defined in the IEEE 802.11s, several resource reservation techniques have been also proposed for IEEE 802.11/11s networks. Resource reservation consists of ensuring enough bandwidth and/or channel access opportunities for RT traffic, in order to guarantee its QoS requirements. The following paragraphs summarize the most interesting and relevant techniques for this purpose, focusing on how RT traffic is modeled and how network interference is considered.

The EDCA with resource reservation (EDCA/RR) was proposed to improve EDCA by allowing resource reservation [103]. It extends the EDCA mechanism by adding distributed resource reservation, admission control, and scheduling. Whenever a station wants to perform a reservation, it must broadcast a request and its QoS requirements must be known by the routing protocol. Resources may only be reserved by high priority traffic, whereas the low priority traffic is processed according to EDCA's admission control. A disadvantage of EDCA/RR is that QoS requirements must be known in advance by the routing protocol. Despite considering an interfering traffic pattern with specific payloads and periods, the authors did not evaluate its impact over the RT communication itself.

A similar approach to EDCA/RR is proposed in [49]. Stations can reserve resources by sending requests, but their neighbors must be informed about future transmissions in order to avoid collisions. This technique itself does not have any admission control nor any traffic differentiation scheme, which turns it unable to provide QoS guarantees [103]. Thus, it is not able to prevent interfering traffic from colliding with frames for which resources were reserved.

In [58], the authors proposed the active neighbor bandwidth reservation (AC-ANBR) as a bandwidth reservation technique. RT traffic is admitted by guaranteeing QoS for all message streams based on active neighbor bandwidth. The proposed technique estimates the available bandwidth of each node and the required bandwidth of each new message stream in order to avoid RT traffic from overusing the available bandwidth resources. Despite the enhancement of the network bandwidth usage, the authors did not consider the impact of interference traffic over the RT communication.

The distributed end-to-end allocation of time slots for real-time (DARE) protocol is a scheme that performs end-to-end reservations for RT traffic [52]. It operates at MAC sublayer by periodically reserving time slots in nodes along a path. It employs a RTS/CTS-based scheme to perform end-to-end time slot reservations. This protocol offers reliable and efficient support for QoS applications, by providing constant throughput and lower and stable end-to-end delay for a reserved RT message stream. The main disadvantage of DARE is the complex and inefficient mechanism for multiple reservations, where a requested reservation may conflict with previously existing ones [103].

Timestamp-ordered MAC (TMAC) is a MAC protocol that aims to improve packet scheduling fairness in WMNs [54]. TMAC measures packet age by means of timestamps and considers it as the metric for prioritization. These timestamps enforce a local ordering among neighboring nodes. TMAC employs a polling scheme by means of modified RTS/CTS control frames. A transmitter polls its neighboring nodes in a parent-child relationship, seeking to confirm if they do not have older packets awaiting for transmission. This polling scheme ensures that a node cannot starve its children at the cost of its own transmission. Despite the improved performance regarding the resource allocation in the network, TMAC only performs the local ordering considering its adjacent neighbors. Consequently, non-adjacent nodes may still interfere in the scheduling scheme and degrade its performance, since RTS/CTS can suffer from unpredictable delays of uncontrolled traffic in the network.

Regarding the optional MCCA scheme, although being able to provide prioritized medium access for RT traffic, Krasilov et al. in [43] have shown that it may suffer from the external interference impact since the non-MCCA mesh STAs are not aware of MCCA reservations. The authors proposed an improved reservation allocation vector (RAV) setup called directional RAV (DRAV) in order to avoid the problem of ACK-induced interference, which consists of a collision between an ACK frame and a reservation. The DRAV scheme forbids a mesh STA to start an EDCA-TXOP if it crosses any MCCA reservation.

As MCCA only performs single-hop reservations, the reservation-based HWMP (R-HWMP) has been proposed as a bandwidth reservation protocol that performs end-to-end reservations among several mesh STAs [51]. R-HWMP modifies the HWMP control frames by introducing some of the flow specification concepts of resource reservation protocol (RSVP) [117]. In the path discovery procedure, the R-HWMP evaluates the number of required slots for each flow transmitted from a specific source. Then, it uses the slot information to find available paths from the source to the destination. Nevertheless, this technique may also suffer from the impact of uncontrolled interferences, since the required slots may be unavailable at the moment of path discovery or frames transmission.

As it can be drawn from the aforementioned works, most of the authors do not consider the impact of interfering traffic over the RT communication behavior. A relevant exception is the work presented in [43], where a performance assessment similar to the one done in this work is presented. The main difference is that in [43], the authors define the prioritized traffic to be transmitted using the optional MCCA, whereas the interference traffic is transmitted using EDCA background class. The evaluation assessment shows that MCCA scheme is impacted by the coexistence of EDCA traffic, due to the ACK-induced interference.

Contrarily to the work presented in [43], the main motivation for this work is to assess the performance of the standard EDCA scheme by itself when the medium is shared between prioritized traffic and non-RT traffic in a WMN, both supported by stations implementing the EDCA mechanism, as defined in the standard. We aim to identify the most relevant EDCA limitations in what concerns the support of RT message streams in real-world WMNs.

4.4 Problem formulation

We assess the behavior of a mesh network when RT traffic (traffic generated by high priority applications) and HTTP traffic (interference traffic) share the same wireless channel. The goal of this work is to assess how the network can reliably support RT communication under this mixed traffic condition.

Four RT message streams were considered in a mesh communication scenario with small fixed-sized messages of 80 and 300 bytes and constant periodicities of 50 and 200 ms. The deadlines of RT message streams were considered equal to the periods.

The non-RT interference traffic was modeled to mimic a hypertext transfer protocol (HTTP) conversation [118]. It works as a request-response protocol in the client-server computing model. Clients send requests to a server, which returns responses with the requested content. Usually, the requested content contains several objects (e.g., images, text, videos, or audio). Thus, once a server receives a request, it answers with one or multiple objects, which constitute several bursts of data.

HTTP traffic was divided into sessions with active and inactive periods, which represent webpage downloads and intermediate reading times. The reading times were considered as the interval between client requests.

To mimic the HTTP conversation behavior, it was considered a client side and a server side. Table 4.2 summarizes the parameters used to define the HTTP traffic model. The HTTP traffic uses the transmission control protocol (TCP) as the transport-layer protocol.

The client side was characterized by request size and request interval parameters. According to the literature [119–121], the typical mean size of requests is 300 bytes, varying from 10 to 2,500 bytes. A truncated log-normal distribution was used to represent this interval. The mean request interval depends on the user-client behavior. A user can request a page and spend a considerable amount of time until making a new request or it can request several pages in a short interval. This behavior was modeled according to a Poisson process with a selectable mean value, i.e., during the simulation process, this mean value will be manually selected according to the desired interference load.

The server side was characterized by a number of objects and their size and response delay parameters. According to [121], the number of objects was represented by a truncated Pareto distribution with mean of 5.64, being 2 the minimum number of objects per page and 50 the maximum. The size of each object has a mean of 7,800 bytes and varies from 50 bytes to 2 Mbytes. A log-normal distribution was used to represent this interval. The server response delay (i.e., parsing time) was modeled by a Poisson process with a mean of 130 ms.

To summarize the HTTP traffic model, a client sends requests varying from 10 to 2,500 bytes according to a specified periodicity (modeled by a Poisson process) and once the server receives

Table 4.2 HTTP traffic parametrization.

Parameter	Statistical characterization
Client request size	Truncated log-normal distribution: $\mu = 5.61$, $\sigma = 0.47$ mean = 300 bytes min = 10 bytes, max = 2,500 bytes
Client request interval	Truncated Poisson process: mean = variable max = 30 s
Server response object size	Truncated log-normal distribution: $\mu = 6.17$, $\sigma = 2.36$ mean = 7,800 bytes min = 50 bytes, max = 2 Mbytes
Number of objects per server response	Truncated Pareto distribution: mean = 5.64 min = 2 objects, max = 50 objects
Server response delay	Truncated Poisson process: $\lambda = 7.69$ mean = 130 ms max = 250 ms

a request, it responds after approximately 130 ms with bursts of multiple objects varying from 50 bytes to 2 Mbytes.

To assess if the WMN can reliably support RT traffic in the presence of HTTP interference traffic, we consider that at least 85% of deadlines must be met. If the ratio of deadline misses is greater than 15%, the WMN is considered as not being able to support RT communication. This threshold is called *deadline miss threshold* (DMT).

For such purpose, two different simulation assessments were considered: 1) with maximum priority traffic separation - where real-time traffic is defined to be transmitted at the highest EDCA priority class *voice*, while the non-RT interference traffic is transmitted at the lowest EDCA priority class *background*; 2) with mixed priority traffic separation - where real-time traffic is kept at the same class voice, but the non-RT interference traffic is transmitted using multiple priority classes: 30% is transmitted using *voice*, 30% *video* and 40% *background* classes.

Finally, a sensitivity analysis of the WMN behavior has been made in order to analyze the effects of varying EDCA contention and HWMP routing protocol parameters. The target of this third simulation assessment is to provide some useful insights on the setting-up of specific protocol parameters and to assess the impact of such parametrization upon the real-time behavior of the WMN.

This set of simulations is a step forward to the assessment of the capability of IEEE 802.11s WMNs to support real-time communication when the wireless channel is shared with non-RT traffic sources.

4.5 Simulation scenarios

A square grid topology with 25 stationary stations disposed in an area of 128 × 128 m was considered to create a mesh network scenario (Figure 4.1). A stationary grid was selected in order to guarantee that the network is well-balanced.

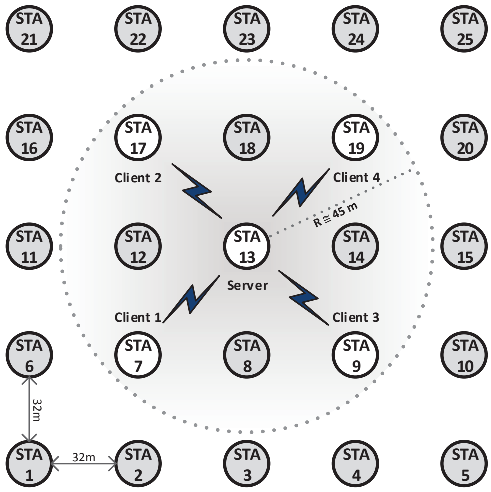

Figure 4.1 5 × 5 stationary grid topology. The circle represents the transmission range of central node.

Considering a grid topology, it is important to determine the combination of distance among nodes, which defines the grid density, and the PHY parameters, as antenna gain, data rate, and transmission power. If these parameters are not correctly specified, the mesh network will not be able to be established or it will suffer from instability issues.

If the mesh network is too dense, i.e., if mesh STAs are placed too close from each other, the packet collision rate may become so high that mesh traffic will suffer from unpredictable delays and losses. On the other hand, if the mesh network is too sparse, peer links may become unstable or never established. Besides, if these parameters allow a mesh STA to directly communicate with non-adjacent neighbors, peer links that may be established with that neighbors may become unstable and increase the mesh network traffic, once the links will be frequently opened and closed.

Based on this argumentation, the antenna gains of mesh STAs in the grid were defined to reach just their adjacent neighbors in order to avoid mesh peering instability due to a higher network density. For such purpose, all mesh STAs operate in IEEE 802.11g standard, with the PHY/MAC parameters as defined in Table 4.3.

Table 4.3 IEEE 802.11g PHY/MAC parameters.

Parameter	**Description**	**Value**
Data rate	Constant data rate (no rate adaptation)	24 Mbps
Basic rate	—	6 Mbps
Channel number	Fixed channel number	6 (2.437 GHz)
Channel width	—	20 MHz
Energy detection threshold	—	−96 dBm
Cca mode 1 threshold	Clear channel assessment threshold	−99 dBm
Antenna type	—	Omnidirectional
Tx/Rx gain	Antenna gain for transmission/reception	1.0 dBi
Tx power	Transmission power level	16.0206 dBm (40 mW)
Rx noise figure	SNR degradation in the receiver	7 dB
Propagation loss model	—	Log-distance
Error rate model	—	Nist OFDM [122, 123]
$\mathrm{aCW}_{\mathrm{min}}$	Minimum contention window size	15
$\mathrm{aCW}_{\mathrm{max}}$	Maximum contention window size	1,023
aSlotTime	Slot time duration	20 µs
T_{SIFS}	Short interframe space (aSIFSTime)	10 µs
T_{SYM}	Symbol interval (BPSK-OFDM)	4 µs
T_{SIG}	Signal BPSK-OFDM symbol duration	4 µs
T_{SIGEX}	Signal extension duration	6 µs
T_{PRE}	PLCP preamble duration	16 µs
T_{ACK}	ACK transmission duration	34 µs
N_{DBPS}	Number of bits per OFDM symbol	96 bits
$\mathrm{MAC}_{\mathrm{header}}$	MAC header size with QoS	26 bytes

The evaluated scenarios consider four RT message streams traversing the mesh network. These streams use user datagram protocol (UDP) as the transport-layer protocol. Different message sizes and periodicities, as well as different sources and destinations, were selected in order to evaluate their behavior in different scenarios. Table 4.4 presents the RT message streams definition.

Table 4.4 Real-time message streams definition.

Message stream	**Mesh source**	**Mesh destination**	**Message size (bytes)**	**Periodicity (ms)**
1	STA 1	STA 25	80	50
2	STA 21	STA 5	80	200
3	STA 25	STA 1	300	200
4	STA 5	STA 21	300	50

In what concerns the interference model, five mesh STAs were defined to implement the

HTTP traffic model, being one server and four clients. In order to provide an interference equally distributed across the mesh network, the interfering nodes were selected from the middle of the mesh grid, as illustrated in Figure 4.1. The HTTP server is the mesh STA 13, and the HTTP clients are mesh STAs 7, 17, 9, and 19.

The simulation experiments were run in simulation batches with a duration of 400 s, being the first 200 s considered for the mesh discovery process. The path selection is performed by the HWMP in proactive mode, where a mesh STA is selected as root in order to coordinate the path selection in the network.

4.5.1 Network utilization model

To determine the network load caused by the HTTP interference traffic, we adapted the utilization model presented in [124]. The network utilization (U) corresponds to the intervals where the wireless channel is occupied by the transmission of MAC service data units (MSDUs) of interfering stations. Let $C = \{c_1, c_2, \ldots, c_m\}$ denotes the set of channel occupancy intervals of MSDUs transmission and $P = \{p_1, p_2, \ldots, p_m\}$ denotes the set of corresponding periodicities, where m is the number of transmitted MSDUs. U can be computed as follows:

$$U = \sum_{i=1}^{m} \left(\frac{c_i}{p_i} \right), \tag{4.3}$$

where c_i and p_i represent the channel occupancy of a single $\text{MSDU}_{(i)}$ transmission and its corresponding periodicity, respectively. It is important to note that p_i is the periodicity value generated by the Poisson process that models the client request interval.

Considering the previously presented HTTP model, c_i must consider the channel occupancy intervals where clients send requests to server and it sends responses to clients. Thus, c_i can be defined as follows:

$$c_i = c_{i_{\text{(client)}}} + c_{i_{\text{(server)}}}, \tag{4.4}$$

where $c_{i_{\text{(client)}}}$ and $c_{i_{\text{(server)}}}$ are the channel occupancy intervals of MSDUs transmitted by a client and by the server, respectively, both defined as follows:

$$c_{i_{\text{(client)}}} = T_{\text{DATA}_{(i)_{\text{(client)}}}} + T_{\text{SIFS}} + T_{\text{ACK}}, \tag{4.5}$$

$$c_{i_{\text{(server)}}} = N_{\text{obj}} \times \left(T_{\text{DATA}_{(i)_{\text{(server)}}}} + T_{\text{SIFS}} + T_{\text{ACK}} \right), \tag{4.6}$$

where $T_{\text{DATA}_{(i)_{\text{(client)}}}}$ is the transmission time of a client request, N_{obj} is the number of objects sent in a server response, and $T_{\text{DATA}_{(i)_{\text{(server)}}}}$ is the transmission time of an object (response) sent by the server. From the IEEE 802.11 standard [11], $T_{\text{DATA}_{(i)}}$ is given by:

$$T_{\text{DATA}_{(i)}} = T_{\text{PRE}} + T_{\text{SIG}} + T_{\text{SIGEX}} + T_{\text{SYM}} \times \left\lceil \frac{16 + 6 + 8 \times \left(\text{MSDU}_{(i)} + \text{MAC}_{\text{header}}\right)}{N_{\text{DBPS}}} \right\rceil . \tag{4.7}$$

Based on the probability distributions that define the client request size and server response object size (Table 4.2), the MSDU size (plus headers from upper layers) was considered as the mean value of that distributions.

We defined different values for the network utilization imposed by the interfering stations, namely: 10%, 30%, and 50%. Based on the above equations, for $U = 10\%$, the client requests are sent with a periodicity of 125 ms, for $U = 30\%$ with 42 ms and for $U = 50\%$ with 25 ms. These periodicity values are used as the mean value for the Poisson process that defines the client request interval.

4.5.2 Performance metrics

As performance metrics, we considered the end-to-end delay and the average ratios of deadline misses and message losses.

4.5.2.a End-to-end delay

The end-to-end delay is of critical importance for RT applications. If a RT message is delayed over its deadline, this message may be considered as being effectively lost. In this assessment, the end-to-end delay (δ_{e2e}) considers all the delays of each sender/receiver (s/r) node pair until reaching the destination. The delay of each s/r node pair in the multi-hop path ($\delta_{s/r}$) is the time interval between the time instant when the acknowledge frame of a message i arrives at the receiver's queue (t_{r_i}) and the time instant when the message i arrives at sender's queue (t_{s_i}). This end-to-end delay calculation includes the processing, queuing, access, and transmission delays and is computed as follows:

$$\delta_{e2e} = \sum_{j=1}^{N_p} \delta_{s/r_{(j)}}, \tag{4.8}$$

$$\delta_{s/r_{(j)}} = \frac{1}{N_m} \times \sum_{i=1}^{N_m} \left(t_{r_i} - t_{s_i}\right), \tag{4.9}$$

where N_m is the number of successfully received messages and N_p is the number of s/r pair nodes.

Summing up, the end-to-end delay is the required time interval to transfer a frame, measured from the moment it joins the sender's queue to the end of the frame transmission at the receiving station.

4.5.2.b Deadline miss ratio

The deadline miss highlights the ratio of messages that exceed their bounded delivery time. In this assessment, the deadline miss ratio (λ) is measured considering the difference between the time instant when a message i was received at the destination and the time instant when message i was sent from the source. If the difference between these time instants is greater than the message periodicity (i.e., its deadline), the message is deemed to have missed its deadline. In addition, a message that is dropped (due to exceeding its transmission attempt count or due to the queue control algorithm) is also deemed to have exceeded its deadline. Thus, the deadline miss ratio is directly affected by the message loss ratio. This ratio is computed as follows:

$$\lambda = \frac{m_{\text{missed}} + m_{\text{dropped}}}{m_{\text{sent}}}, \tag{4.10}$$

where m_{missed} is the total number of successfully received messages that missed their deadline, m_{dropped} is the total number of undelivered messages (that obviously also missed their deadlines), and m_{sent} is the total number of sent messages.

4.5.2.c Message loss ratio

The message loss ratio is defined for a receiving station as the number of dropped messages during a transmission. In this assessment, the message loss ratio (σ) is measured considering the messages that were effectively dropped due to transmission error or due to exceeding the transmission attempt count. It can be computed as follows:

$$\sigma = \frac{m_{\text{dropped}}}{m_{\text{sent}}}, \tag{4.11}$$

where m_{dropped} is the total number of dropped messages and m_{sent} is the total number of sent messages.

4.6 Simulation results

Different communication scenarios have been simulated to assess the behavior of RT traffic when the wireless channel is shared with non-RT traffic generated by a set of interfering stations. For the sake of simplicity, only the results that concern RT traffic will be presented.

4.6.1 Impact of external traffic sources over the end-to-end delay

The first simulation scenario concerns the assessment of the end-to-end delay of four RT message streams, as defined in Table 4.4, when the overall network utilization is increased by a set of interfering stations.

Figure 4.2 illustrates the histogram and the cumulative distribution function (CDF) of end-to-end delay of RT message streams without any interfering traffic sources in the network, where it can be observed the default behavior of RT communication.

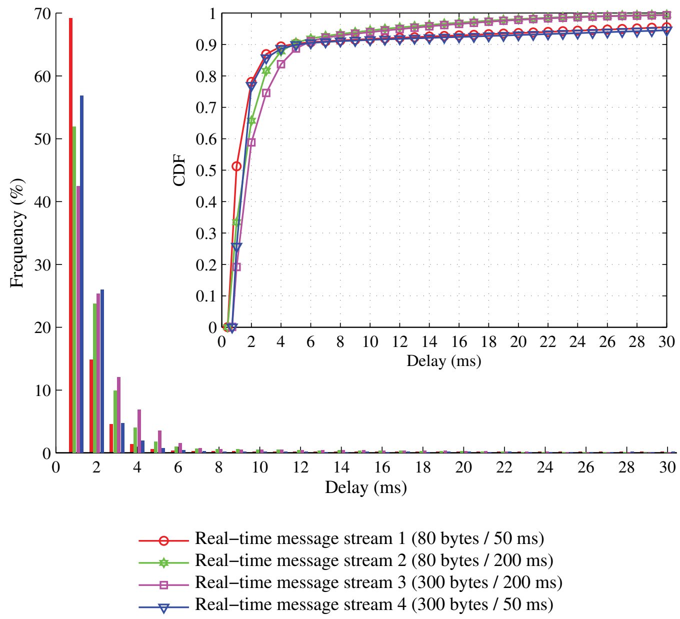

Figure 4.2 Histogram and CDF of end-to-end delay of RT message streams without any external traffic sources.

Based on Figure 4.2, it is possible to notice that RT message streams with the lowest periodicity experiment slightly increased delay, regardless of the message size. This behavior is due to the number of messages that are sent in a shorter period, which are prone to higher delays since the network needs to deal with other traffic and the wireless channel is not always available for such shorter interval requests. However, the difference between the end-to-end delay of the different message streams is negligible.

Regarding the impact of non-RT traffic over the RT communication, Figure 4.3(a),(b),(c) presents the histograms and CDFs of end-to-end communication delay with maximum priority traffic separation between RT traffic and non-RT traffic (as defined in Section 4.4) and Figure 4.3(d),(e),(f) presents the histograms and CDFs of end-to-end communication delay with mixed priority traffic separation between RT traffic and non-RT traffic (also as defined in Section 4.4).

According to the results, it is noticeable that the end-to-end delay of RT traffic increases as the overall network utilization increases. These results clearly show the impact of the interference traffic upon the RT traffic behavior, even for the case when the maximum priority traffic separation is imposed. With a network load equal or greater than 30%, it is clear that the end-to-end delay of all RT message streams is highly affected. For the case when the mixed

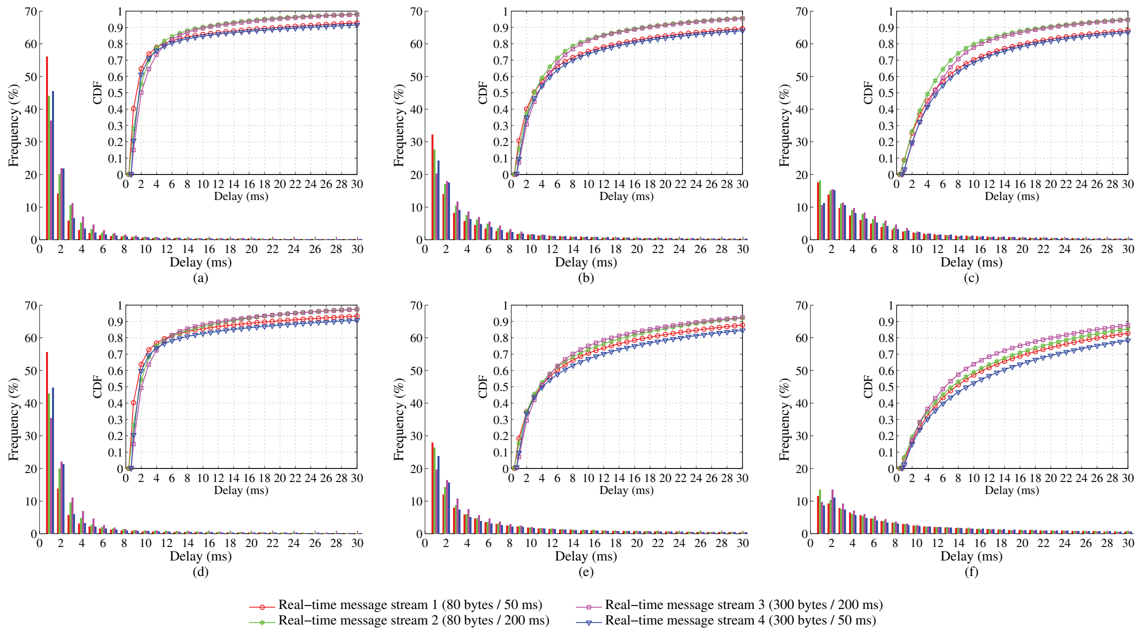

Figure 4.3 Histograms and CDFs of end-to-end delay of RT message streams with external traffic sources. **(a)** 10%, **(b)** 30%, and **(c)** 50% of network utilization with maximum priority traffic separation between RT traffic and non-RT traffic; **(d)** 10%, **(e)** 30%, and **(f)** 50% of network utilization with mixed priority traffic separation between RT traffic and non-RT traffic.

priority traffic separation is imposed, the delay is even more affected when compared to the maximum priority traffic separation. This set of simulations indicates that the mandatory EDCA MAC mechanism, defined in the IEEE 802.11s, is not able to impose the traffic separation required for RT communication when using the default set of parameters, since the non-RT interference traffic (background) affects the RT communication (voice), as the dispersion of the histograms related to a utilization of 30% to 50% is considerably higher.

4.6.2 Impact of external traffic sources over the average ratios of deadline misses and message losses

The second simulation scenario concerns the assessment of average ratios of deadline misses and message losses for the RT message streams. Figure 4.4 illustrates the impact of interference traffic over these metrics.

The deadline miss ratio is directly influenced by both the message loss ratio (Figure 4.4(b),(d)) and the excessive access delay of RT message streams (Figure 4.3). A noticeable increase of deadline misses can be observed, caused by the increasing delay as the network utilization increases.

From the above results, it is possible to notice that maximum priority traffic separation presents less deadline misses when compared to the mixed priority traffic separation. In the

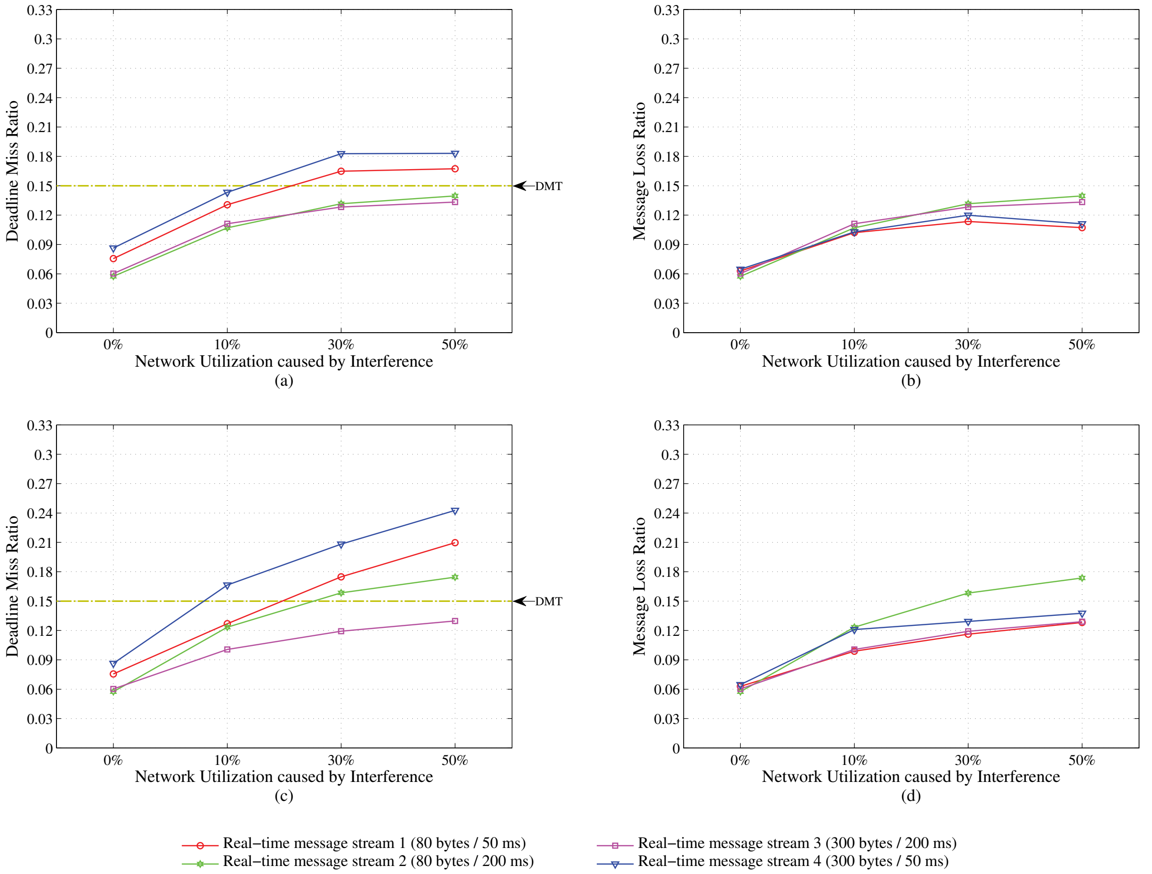

Figure 4.4 Average ratios of deadline misses and message losses of RT message streams. **(a)** deadline miss ratio and **(b)** message loss ratio with maximum priority traffic separation between RT traffic and non-RT traffic; **(c)** deadline miss ratio and **(d)** message loss ratio with mixed priority traffic separation between RT traffic and non-RT traffic.

mixed priority separation scenario, the traffic transmitted at video and voice classes severely impact the deadline miss ratio. Also, message streams with longer periodicity values tend to present less deadline misses, regardless of their size, since they contend for the medium access less frequently. On the other hand, message streams with shorter periodicity values tend to present higher number of deadline misses since there are more messages being transmitted in a shorter time interval, which are therefore more prone to losses.

Considering message streams 1 and 4, which are the streams with shorter periodicity values (Table 4.4), they clearly exceed a DMT value of 15% (target defined in Section 4.4) when the network utilization is greater than approximately 12% and 21%, respectively, even for the case when the maximum priority traffic separation is imposed. This behavior worsens when the mixed priority traffic separation is imposed, where the DMT is exceeded when the network utilization is greater than approximately 8% and 19%, respectively.

Considering message streams 2 and 3, which are the streams with longer periodicity values, they do not exceed the DMT value with the maximum priority traffic separation when the network utilization is less than or equal to 50%. Also, it is important to note that deadline misses are due to message losses, as can be seen in the Figure 4.4(a),(b). This means that all successfully transmitted messages arrived on time at the destination. However, for the mixed priority traffic separation scenario, the message stream 2 slightly exceeds the DMT, for the case where the network utilization is greater than approximately 26%. Once again, the deadline misses of message stream 2 are caused by message losses, as can be extracted from Figure 4.4(c),(d). This result indicates that streams with longer periodicity values suffer less impact when compared with streams with shorter periodicity values, where deadline misses are caused essentially by message losses.

The results suggest that RT communication performance is highly dependent on the traffic type and on the imposed network utilization. Also, the periodicity values of message streams play an important role in the RT communication performance, regardless of messages size. Thus, the IEEE 802.11s standard with the mandatory EDCA scheme may only reliably support RT traffic with shorter periodicity values when the network utilization is below 20% and the interference traffic occurs at lower priority classes. However, when high priority classes are used to transmit interference traffic, the RT communication is severely impacted by the network utilization, since EDCA is not able to provide an acceptable service differentiation.

4.6.3 Tuning EDCA and HWMP parameters

Considering that we have full control upon the parameters of RT stations, it is reasonable to propose the selection of adequate parameters to improve the RT message streams transmission. Therefore, in this third scenario, we make a sensitivity analysis to assess the effects of varying EDCA contention and HWMP routing parameters upon the RT communication behavior. The set of parameters that are subject to analysis are: the CW size of the EDCA mechanism and the *traversal time* and *path lifetime* of the HWMP.

4.6.3.a Varying the contention window size

As seen in the previous section, the EDCA mechanism presents a poor performance to support RT traffic when the wireless channel is shared with interfering traffic sources, notably when the overall network utilization is above 20%. In order to investigate the impact of EDCA parameters in the WMNs communication behavior, we assess the effects of varying the contention window size used to transmit RT traffic. Similarly to the assessment presented in [107], we examined all the possible combinations of aCW_{min} and aCW_{max} between 1 and 1,023. We chose to reproduce the scenario where the network utilization is 30% and the mixed priority traffic separation is imposed between RT traffic and interference traffic. Tables 4.5 and 4.6 present the main results for real-time message streams 1 and 2 and for streams 3 and 4, respectively. For the sake of presentation, we highlighted the results for the EDCA voice class.

Table 4.5 Effects of varying aCW_{min} and aCW_{max} upon RT message streams 1 and 2.

$\mathbf{aCW_{min}}$	$\mathbf{aCW_{max}}$	**Average end-to-end delay (ms)**		**Deadline miss ratio (%)**		**Message loss ratio (%)**	
		Stream 1	**Stream 2**	**Stream 1**	**Stream 2**	**Stream 1**	**Stream 2**
1	3	11.27	8.36	16.2	12.5	10.1	12.5
1	7	12.15	8.76	16.7	12.3	10.1	12.3
1	15	12.47	9.03	16.8	12.8	10.1	12.7
⋮	⋮						
1	1,023	13.62	9.28	16.7	13.1	9.5	13.0
3	*7*	*13.20*	*9.36*	*16.6*	*12.1*	*9.8*	*12.1*
3	15	13.36	9.59	16.4	12.2	9.6	12.2
3	31	13.90	9.74	17.0	12.3	10.0	12.3
⋮	⋮						
3	1,023	13.03	9.79	15.9	12.3	9.5	12.3
7	15	14.30	11.02	16.7	12.2	9.9	12.1
7	31	16.68	11.68	17.5	11.8	9.6	11.7
7	63	16.31	11.70	17.3	12.0	9.5	11.9
⋮	⋮						
7	1,023	16.84	12.72	17.7	12.8	9.8	12.6
15	31	21.92	14.79	19.9	12.6	9.9	12.4
⋮	⋮						
15	1,023	24.08	15.42	20.6	12.5	9.7	12.2
⋮	⋮						
255	1,023	220.41	109.79	63.2	26.2	11.7	12.8
511	1,023	542.52	279.33	83.7	50.2	14.5	14.2

The italicized values present the RT communication performance when using EDCA voice class, i.e., $aCW_{min} = 3$ and $aCW_{max} = 7$.

Contrarily to the results observed in [107], where it is highlighted a performance improvement with larger CW values (e.g., $aCW_{min} = 15$ and $aCW_{max} = 31$) over the default voice class (i.e., $aCW_{min} = 3$ and $aCW_{max} = 7$), in this mesh scenario smaller CW values (e.g., $aCW_{min} = 1$ and $aCW_{max} = 3$) present better performance over the voice class. It is important to note the assessment presented in [107] considers a single-hop *ad hoc* network with no hidden terminals. In this assessment, due to the multi-hop communication and grid topology, there are several hidden terminals in the WMN. However, the interference caused by a transmitting station affects only the stations in the related coverage area, i.e., other message streams can be simultaneously transmitted in another network area. Consequently, there is a performance degradation of RT communication as the size of CW increases. Messages with higher CW values spend more time in EDCA queues, since they backoff for longer time intervals and consequently the deadline miss ratio increases.

Table 4.6 Effects of varying aCW_{min} and aCW_{max} upon RT message streams 3 and 4.

aCW_{min}	aCW_{max}	Average end-to-end delay (ms)		Deadline miss ratio (%)		Message loss ratio (%)	
		Stream 3	Stream 4	Stream 3	Stream 4	Stream 3	Stream 4
1	3	7.34	15.17	10.9	20.0	10.9	12.4
1	7	7.87	15.96	11.0	19.8	10.9	11.7
1	15	8.15	17.07	10.5	20.9	10.5	11.9
⋮	⋮						
1	1,023	8.13	18.11	11.2	21.2	11.1	12.4
3	*7*	*8.02*	*16.70*	*11.0*	*20.4*	*11.0*	*12.2*
3	15	8.72	16.91	10.9	20.0	10.9	11.7
3	31	8.88	16.65	11.0	20.1	10.9	11.9
⋮	⋮						
3	1,023	8.30	16.86	10.5	20.5	10.5	12.1
7	15	9.79	18.01	10.4	20.6	10.4	11.8
7	31	10.25	19.21	11.5	21.6	11.4	12.4
7	63	10.55	19.59	11.0	21.3	11.0	11.9
⋮	⋮						
7	1,023	10.76	20.03	11.3	21.8	11.1	12.4
15	31	13.59	24.33	10.9	23.2	10.7	11.7
⋮	⋮						
15	1,023	14.56	26.03	10.9	23.2	10.6	11.2
⋮	⋮						
255	1,023	106.46	215.28	24.5	63.4	11.2	13.9
511	1,023	283.65	527.28	48.7	84.0	11.7	16.5

The italicized values present the RT communication performance when using EDCA voice class, i.e., $aCW_{min} = 3$ and $aCW_{max} = 7$.

4.6.3.b Varying HWMP parameters

The HWMP routing protocol has a set of protocol parameters that are essential for the path management and directly impacts on the communication performance in the WMN. One of those parameters is the traversal time (defined by the attribute *dot11MeshHWMPnetDiameterTraversalTime*), an upper bound for the time interval to propagate an HWMP element across the mesh network. Basically, whenever a frame takes a time interval to traverse the mesh that is longer than the traversal time, it is discarded and no longer delivered at its destination.

Another HWMP parameter is the path lifetime (composed of the attributes *dot11MeshHWMPactivePathToRootTimeout* and *dot11MeshHWMPactivePathTimeout*), which is a parameter that specifies the time during which a mesh STA shall consider the forwarding information to the root mesh STA to be valid (proactive mode) and to any other mesh STA (reactive mode), respectively. Basically, the path lifetime defines an upper bound for the path duration; whenever it expires, the path is reset and a new path discover procedure is initiated.

These two HWMP parameters are the most relevant when considering the RT communication behavior in a WMN. Therefore, the sensitivity analysis performed in this chapter addresses specifically these two network parameters and its effects over the communication performance. Once again, it was considered a communication scenario with a network utilization of 30% and a mixed priority traffic separation between the real-time traffic and the interfering HTTP traffic.

The default values of HWMP parameters are defined in Table 4.7 and the communication performance with these values can be observed in Tables 4.5 and 4.6 for default EDCA voice class parameters, i.e., $aCW_{min} = 3$ and $aCW_{max} = 7$. For the sake of simplicity, these values will not be repeated in Tables 4.8, 4.9, and 4.10, which present the communication performance when the default values of HWMP parameters are changed.

Table 4.7 HWMP default parameters.

Parameter	**Value**
Path lifetime	5 s
Traversal time	500 ms

When varying the traversal time value (see Table 4.8), it is possible to notice an improvement in the communication performance. For example, considering the message stream 4, the message loss ratio decreases from 12.2% (when using the default traversal time value) to 10.7% (when decreasing the traversal time value to 100 ms). The opposite occurs when the traversal time value is increased to 1,000 ms. Therefore, to optimize the RT communication behavior it is recommended to set the traversal time to the maximum message stream period value, i.e., 200 ms for this communication scenario.

Table 4.8 RT communication performance with different values for traversal time.

	Traversal time (ms)							
	100	**1,000**	**100**	**1,000**	**100**	**1,000**	**100**	**1,000**
	Stream 1		**Stream 2**		**Stream 3**		**Stream 4**	
Average end-to-end delay (ms)	10.11	14.43	6.97	9.76	7.29	9.02	10.35	17.12
Deadline miss ratio (%)	13.6	17.6	10.6	15.0	9.4	12.2	14.8	20.7
Message loss ratio (%)	9.6	12.4	10.6	15.0	9.4	12.2	10.7	13.8

Table 4.9 presents the results of varying the path lifetime value from 5 s to 1 s and 10 s. When the path lifetime value is lower than the default value, it is possible to notice an

improvement in the RT communication performance. This is an expected result, since to reliably support real-time traffic, the path forwarding information should stay valid as long as possible. Otherwise, new path discovery procedures would be frequently performed, which degrades the RT communication performance. Therefore, contrarily to the commonly used HTTP applications, for RT traffic transmission, it is desirable to establish and maintain the forwarding paths valid as long as possible.

Table 4.9 RT communication performance with different values for path lifetime.

	Path lifetime (s)							
	1	10	1	10	1	10	1	10
	Stream 1		Stream 2		Stream 3		Stream 4	
Average end-to-end delay (ms)	34.27	8.54	10.99	6.66	12.89	6.57	40.44	9.72
Deadline miss ratio (%)	50.9	9.7	46.6	9.0	42.6	6.7	49.9	12.7
Message loss ratio (%)	33.3	6.8	46.5	9.0	42.5	6.7	29.4	9.0

Based on the best CW, traversal time and path lifetime values extracted from the previous simulation scenario, we repeated the simulation from the third scenario. Table 4.10 illustrates the performance metrics when considering this scenario with aCW_{min} = 1 and aCW_{max} = 3, traversal time = 200 ms and path lifetime = 10 s. As a result of this sensitivity analysis, we may conclude that by carefully setting the CW, traversal time and the path lifetime parameters we may significantly increase the quality of service provided to the RT traffic supported by the WMN.

Table 4.10 RT communication performance with best contention and routing parameter values.

	Stream 1	Stream 2	Stream 3	Stream 4
Average end-to-end delay (ms)	6.80	5.30	5.44	8.35
Deadline miss ratio (%)	8.20	7.05	6.13	9.59
Message loss ratio (%)	5.49	7.03	6.11	6.26

4.7 Conclusions

This chapter presents a simulation assessment of the impact of non-real-time (non-RT) traffic sources upon RT communication in IEEE 802.11s WMNs. A set of simulation experiments have been conducted in ns-3, to assess the RT communication behavior when the wireless channel is shared with external interferences.

From the simulation results, it can be observed that the RT communication behavior is directly affected by the presence of non-RT traffic sources. The default parameter values used for EDCA are not adequate to provide the required service differentiation, as the EDCA mechanism is not able to separate the higher priority traffic from the traffic transmitted at lower priority classes. When increasing the network utilization, it can be observed a degradation of the performance metrics, indicating that the default parameter values should be set differently.

Therefore, a sensitivity analysis has been performed to evaluate the impact of some EDCA/HWMP key parameters upon the RT communication behavior. By carefully setting the EDCA CW size and the HWMP traversal time and path lifetime parameters, it was possible to enhance the RT communication behavior and consequently to improve the support of RT communication in WMNs. Basically, it could be observed that the RT communication behavior is significantly improved from the usage of: a) smaller CW sizes for the EDCA mechanism, b) larger path lifetime values for the HWMP protocol, and c) mesh traversal times adjusted to the longest periodicity value in use for the supported RT message streams.

CHAPTER 5

A multi-hop resource reservation scheme to support real-time communication in IEEE 802.11s wireless mesh networks

In this chapter, the new Mesh Resource Reservation (MRR) scheme is proposed intended to support real-time (RT) communication in 802.11s wireless mesh networks (WMNs), when the wireless channel is shared with uncontrolled non-RT traffic sources. The MRR scheme controls the channel access of neighboring stations of an RT path, by slowing-down their channel contention during reserved intervals. The objective of this scheme is to reduce the surrounding interferences over the real-time communication in order to meet the QoS requirements. This chapter is a reproduction of the contents of the following paper:

C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. A multi-hop resource reservation scheme to support real-time communication in IEEE 802.11s wireless mesh networks. SUBMITTED FOR PUBLICATION IN *Ad Hoc Networks*, Elsevier, 2015.

Abstract

With the introduction of IEEE 802.11s standard, the deployment of wireless mesh networks in industrial WLANs became easier. However, there are still some impairments on QoS provisioning for delay sensitive applications in WMNs. These impairments are mainly related to the MAC mechanisms, which are not able to adequately provide service differentiation for real-time (RT) traffic in multi-hop scenarios. This issue is especially acute when the wireless channel is shared with uncontrolled traffic sources. In this context, this chapter proposes a multi-hop resource reservation scheme targeting the support of RT traffic in WMNs. The proposed scheme performs end-to-end reservations of time intervals, during which the neighboring stations of an RT path are compelled to contend for the channel in a slowdown

contention mode. The objective is to reduce the surrounding interferences over the RT traffic in order to meet its QoS requirements. The effectiveness of the proposed scheme is assessed through an extensive set of simulations, and it is compared with the MAC mechanisms defined by the IEEE 802.11s standard, and with other resource reservation scheme available in the literature. The simulation results show that it is possible to diminish the impact of interferences over RT traffic in multi-hop scenarios by means of resource reservation schemes.

5.1 Introduction

Wireless mesh networks (WMNs) have emerged as a promising technology for next generation wireless networking. WMNs are decentralized, easy to deploy, and characterized by dynamic self-organization, self-configuration, and self-healing properties [9]. WMNs enable rapid deployment with low-cost backhaul, where the network coverage can be extended through a wireless multi-hop relaying backbone [10].

Typical WMNs deployment implements packet forwarding at network layer [102]. Instead, the IEEE 802.11s standard specifies a data link layer WMN that extends the coverage of traditional 802.11 wireless local area networks (WLANs), and supports a larger diversity of wireless technologies [11].

With the WMN capabilities introduced by the IEEE 802.11s specification, the traditional 802.11 WLANs are improved regarding the suitability for applications requiring resilience and redundancy (such as smart grids, industrial communication, and public safety), and peer-to-peer communication (such as home networks, content-sharing, and gaming).

Despite the benefits of 802.11s-based WMNs, there are still some impairments on quality of service (QoS) provisioning for delay sensitive applications. The main drawbacks are related to the medium access control (MAC) schemes, which have been originally proposed for single-hop communication scenarios. Consequently, they do not perform adequately when applied to multi-hop scenarios [6, 19, 77]. The default IEEE 802.11s MAC, which is based on the enhanced distributed channel access (EDCA), presents poor performance due to throughput degradation as the number of hops increase [125, 126], and also due to the hidden terminal problem, which increases the collision probability [23, 127]. In addition, EDCA is not able to provide service differentiation for prioritized traffic when the channel is shared with uncontrolled traffic sources [42], or when dealing with mobile stations [128]. The optional IEEE 802.11s MAC, which is based on the mesh coordination function (MCF) controlled channel access (MCCA), intends to provide collision-free and guaranteed channel access during reserved time slots, fails to achieve the desired objective, since its performance is highly affected by the contention of non-MCCA mesh stations [43]. Moreover, the MCCA was designed to perform reservations just between adjacent mesh stations (i.e. single-hop reservations), and due to this, by default, it is not able to provide end-to-end QoS guarantees.

The deployment of IEEE 802.11s WMNs over WLANs in industrial environments is a challenging task [4] and it became a research area of interest. In such environments, real-time (RT) data (typically small-sized messages) must be periodically transmitted among sensors, controllers, and actuators according to strict transmission deadlines [12]. Since the IEEE 802.11s MAC mechanisms are not able to adequately provide QoS guarantees for prioritized traffic, the deployment of RT services over WMNs require additional QoS mechanisms. Most of current RT applications may benefit from a priori reservation of network resources (e.g. link bandwidth, time slots, and channels) in order to meet their QoS requirements. Within this context, several research efforts targeted the RT communication support by means of resource reservation (RR) techniques over multi-hop networks [49, 51, 52, 54, 129].

However, most part of the proposed RR techniques are focused on the RT traffic itself, regardless of the interference of non-RT traffic sources. Usually, the authors focus on the proposed techniques and their performance, and, in some cases, relevant simplifications are made (e.g. ideal wireless channel conditions are considered [106]). Consequently, the related assessments may not reflect the real-world behavior, which is usually prone to interferences of non-RT traffic sources that may impact in the communication performance, as highlighted in [42, 107]. A relevant exception is presented in [130], which considers the interference of non-adjacent neighboring nodes and adapts the reservations according to the estimation of channel conditions.

In this chapter, we propose the Mesh Resource Reservation (MRR), a multi-hop reservation scheme targeting the RT communication support in IEEE 802.11s WMNs. MRR operates at MAC sublayer by performing end-to-end reservations of time intervals, during which the neighboring stations of an RT path are compelled to contend for the channel in a slowdown contention mode. Contrary to other RR schemes available in the literature, which block the transmissions in the neighborhood of a reservation by setting the network allocation vector (NAV), in the MRR scheme the neighboring stations must increase the channel contention values in order to defer their frames transmission. The objective of this scheme is to reduce the surrounding interferences and the impact of non-RT traffic sources over the RT communication. Besides, blocking mechanisms are unrealistic in real-world scenarios, and it can be restrictive to the overall network communication performance when considering industrial environments, since there are several types of applications that may present malfunctions due to the traffic blockage effects.

A set of simulation experiments, using the network simulator 3 (ns-3), were defined aiming to reproduce real-world scenarios with uncontrolled traffic sources in the WMN. The performance of MRR scheme was compared with EDCA and MCCA schemes [11], and also with the distributed end-to-end allocation of time slots for real-time (DARE), proposed by Carlson et al. [52]. The results indicate that the IEEE 802.11s MAC may benefit from the use of RR schemes to provide end-to-end QoS guarantees for RT traffic.

The major scientific contributions of this chapter can be summarized as follows:

1. A new RR scheme proposed for QoS provisioning for RT traffic in an end-to-end basis, which is able to deal with uncontrolled traffic sources in the network;
2. An adapted MCCA scheme to perform end-to-end reservations in multi-hop scenarios;
3. An improved MCCA scheme, named as MCCA+MRR, which includes some of the MRR properties to perform reservations without blocking the neighboring stations;
4. An extensive assessment of the proposed RR schemes in order to evaluate their effectiveness for QoS provisioning for RT traffic in multi-hop scenarios, when the communication channel is shared with uncontrolled traffic sources.

The remainder of this chapter is organized as follows. Section 5.2 presents an overview of the IEEE 802.11s WMN standard, focusing on the MAC mechanisms functionalities. Section 5.3 reviews the related work on resource reservation schemes. Section 5.4 presents the proposed Mesh Resource Reservation (MRR) scheme. Sections 5.5 and 5.6 describe the problem and the simulation model used in the assessment of the RR schemes. Section 5.7 presents an analysis of the results. Finally, some conclusions are drawn in Section 5.8.

5.2 IEEE 802.11s overview

The IEEE 802.11s introduces frame forwarding at MAC level that uses a multi-hop wireless relaying infrastructure, where nodes cooperatively maintain the network connectivity [11]. Every node can work as a relaying node, forwarding frames in behalf of its neighbors. The mesh connectivity is managed by the mesh peering management (MPM) protocol, which is responsible to establish, manage, and tear down mesh peer links among mesh stations (STAs).

The default path selection protocol is the hybrid wireless mesh protocol (HWMP), which combines reactive (on-demand) path selection with extensions to enable proactive (tree-based) path selection. The reactive mode is based on the ad hoc on-demand distance vector (AODV) routing protocol, which allows mesh STAs to communicate in a peer-to-peer basis. In the proactive mode, additional tree building functionality is added to the on-demand mode, by configuring a mesh STA as root of a path tree (formally root mesh STA). The root is responsible to coordinate the path selection by periodically sending proactive information elements to the mesh STAs. HWMP uses radio-aware metrics, being the airtime link metric defined as default, which reflects the amount of channel resources consumed during a frame transmission over a particular link.

The medium access control (MAC) on IEEE 802.11s WMNs is managed by the mesh coordination function (MCF), which schedules the access to the channel by allocating transmission opportunities (TXOPs) to mesh STAs [11]. MCF adopts the enhanced distributed channel access (EDCA) as the mandatory MAC mechanism, which is a contention-based channel access mechanism based on carrier sense multiple access with collision avoidance (CSMA/CA). In addition to EDCA, the MCF defines the optional MCF controlled channel access (MCCA) MAC mechanism, which is a collision-free and guaranteed channel access for QoS-aware traffic. The next subsections present a brief overview of the EDCA and MCCA schemes.

5.2.1 Enhanced distributed channel access (EDCA)

EDCA provides service differentiation by classifying frames from upper layers into four different access categories (ACs), in which frames of different traffic types are mapped according to the application and its QoS requirements: background (BK), best effort (BE), video (VI), and voice (VO) traffic.

For each AC, an enhanced variant of the distribution coordination function (DCF), called EDCA function (EDCAF), contends for TXOPs using a set of EDCA parameters. These EDCA parameters modify the backoff process with individual interframe spaces and contention windows (CWs) per AC.

During the contention phase, each station senses the channel in order to start the frames transmission. If the channel is sensed idle for at least an arbitration interframe space (AIFS[AC]) period, a station transmits its frames. Otherwise, the station initiates a backoff interval in order to avoid collisions. The duration of AIFS[AC] is given by:

$$\text{AIFS[AC]} = \text{AIFSN[AC]} \times \text{aSlotTime} + \text{aSIFSTime} \tag{5.1}$$

where AIFSN[AC] defines the number of slot times per AC (where AIFSN[AC] ≥ 2), aSlotTime is the minimum slot duration and aSIFSTime is the short interframe space (SIFS) duration.

5.2.2 MCF controlled channel access (MCCA)

MCCA is a distributed channel reservation scheme designed to reduce frames collision. MCCA-enabled mesh STAs can reserve the channel for prioritized access during predefined intervals, called MCCA opportunities (MCCAOPs). A reservation specifies a regular schedule of MCCAOPs in the delivery traffic indication message (DTIM). The interval between consecutive DTIM beacon frames is divided into slots of 32 μs. A mesh STA transmitting an MCCA setup request frame becomes the owner of the MCCAOP. The receivers of an MCCA setup request frame are the MCCAOP responders. The MCCAOP responders upon receipt of an MCCA setup request check the requested reservation for any conflicting MCCAOP and transmits an MCCA setup reply accepting or rejecting it.

An MCCA setup request contains three reservation parameters: *offset*, *duration*, and *periodicity*. The maximum duration of an MCCAOP is 4,096 μs, which means 128 slots of 32 μs.

The number of MCCAOPs arranged in the DTIM interval is given by the *periodicity* and the *offset* values (Figure 5.1).

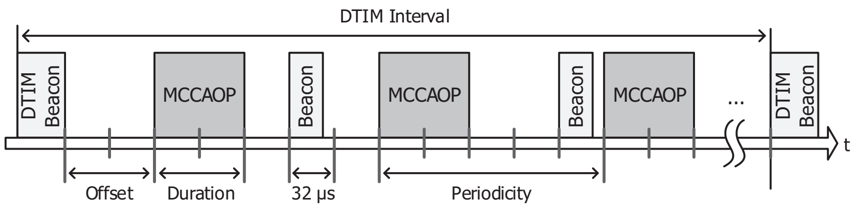

Figure 5.1 An example of MCCAOP reservation, with a set of MCCAOPs arranged in the DTIM interval.

To reduce the probability of conflicting reservations, the MCCAOP owner and the MCCAOP responders periodically advertise their MCCAOP reservations to their neighbors via an MCCAOP advertisement (MADV) frame. The MADV frame consists of a set of periods report which contains the schedule information of MCCAOPs. Based on this schedule information, mesh STAs are able to keep track of MCCAOP reservations, and therefore avoiding reservation conflicts.

Upon the reservation establishment, the MCCAOP owner needs to contend for the channel during the MCCAOP using the EDCA scheme. Only after successfully obtaining an EDCA-TXOP, the MCCAOP owner can initiate its frames transmission. At the beginning of the MCCAOP, when contending for an EDCA-TXOP, the MCCAOP owner experiences no competition from other MCCA-enabled STAs in the neighborhood, since its EDCAF parameters for all ACs are replaced by the minimum contention values, which are AIFSN = 1, $aCW_{min} = 0$, and $aCW_{max} = 31$. In addition, data frames retransmission is disabled during an MCCAOP.

During the MCCAOP, MCCA-enabled mesh STAs that are in the neighborhood of MCCAOP owner and/or MCCAOP responders maintain a reservation allocation vector (RAV) to indicate busy channel for the duration of the MCCAOP. RAV contains an index of future MCCAOPs based on the periods report informed by the MADV frame. To increase the reservation protection, MCCA-enabled mesh STAs set their network allocation vector (NAV) at the first frame exchange sequence in the MCCAOP. If RAV or NAV are active, MCCA-enabled mesh STAs cannot contend for the channel access.

5.3 Related work

Resource reservation (RR) consists of ensuring enough bandwidth and/or channel access opportunities for time-critical applications, in order to guarantee their QoS requirements. In the literature, several RR techniques have been proposed to IEEE 802.11/11s networks aiming to improve the performance of MAC mechanisms and to mitigate their impairments. This section summarizes the most relevant RR techniques, focusing on how RT traffic is modeled and how network interference is considered.

The IETF proposed the integrated services (IntServ) [26] and differentiated services (DiffServ) [27] architectures, seeking to enable end-to-end QoS provisioning in IP-based networks. The IntServ follows a signaled-QoS model, in which the end-hosts announce their QoS requirements to the network, while the DiffServ follows a provisioned-QoS model, in which multiple traffic classes with varying QoS requirements are provided by the network elements. However, when considering the RT communication support in WMNs, the IntServ is not scalable, being restricted to scenarios with few nodes, and the DiffServ only provides best effort delivery. Moreover, neither IntServ nor DiffServ are able to adequately deal with mobile nodes.

To improve the EDCA mechanism, the EDCA with resource reservation (EDCA/RR) is proposed to add distributed resource reservation, admission control, and scheduling [129]. In this mechanism, whenever a station needs to perform a reservation, it must broadcast reservation requests and its QoS requirements must be known by the routing protocol. Resources may only be reserved to high priority traffic, whereas the low priority traffic is processed according to the default EDCA mechanism operation. A disadvantage of EDCA/RR is that it only works for single-hop communication. In addition, despite considering an interfering traffic pattern with specific payloads and periods, the authors did not evaluate its impact over the RT communication itself. A similar approach to EDCA/RR is proposed in [49], where stations reserve resources by sending requests, but their neighbors must be informed about future transmissions in order to avoid frames collision. This technique itself does not have any admission control nor any traffic differentiation scheme, which turns it unable to prevent interfering traffic from colliding with frames for which resources were reserved.

The distributed end-to-end allocation of time slots for real-time (DARE) [52] is an MAC mechanism that reserves time slots for RT traffic in an end-to-end basis. DARE extends the RTS/CTS mechanism to multi-hop scenarios by introducing new control messages: request to reserve (RTR) and clear to reserve (CTR), which are exchanged among nodes in the path towards the destination in order to perform end-to-end reservations. During a reservation, the nodes that are in the neighborhood of the reserved path must abstain from transmission by setting their network allocation vector (NAV), in order to prevent from interfering upon the RT communication. Despite DARE being able to offer reliable and efficient QoS support for DCF scheme (which only provides best effort delivery), its performance with different access categories of EDCA was not assessed by the authors. Moreover, the assessed communication scenario was an IEEE 802.11 mesh-based network, which is significantly different from an IEEE 802.11s WMN.

Timestamp-ordered MAC (TMAC) [54] aims to improve packet scheduling fairness in WMNs. TMAC measures packet's age by means of timestamps and considers it as the metric for prioritization. This chapter proposes to employ a polling scheme by means of modified

RTS/CTS control frames, where a transmitter polls its adjacent neighbors in a parent-child relationship, seeking to confirm if they have older packets awaiting for transmission. This polling scheme ensures that a STA cannot starve its children at the cost of its own transmission. Despite the improved performance, TMAC only performs local ordering considering its adjacent neighbors. Consequently, non-adjacent nodes may still interfere in the scheduling scheme and degrade performance. Moreover, RTS/CTS may suffer from unpredictable delays from uncontrolled traffic sources in the network which disturb the mechanism operation.

In [131], the authors propose an MAC mechanism for 802.11-based networks that optimizes the bandwidth resources usage, aiming the support for triple-play services. It distributes the channel efficiently among stations running different applications, while prioritizing medium access for time-critical applications. The proposed scheme adapts the interframe space and TXOP limit values according to the traffic type and priority. Despite the improvement of fairness in channel usage for both real-time and non-real-time applications with the proposed scheme, the authors did not consider concurrent channel access from uncontrolled traffic sources in the network.

Regarding the optional MCCA scheme, Krasilov et al. [43] have shown that it may suffer from the external interference impact since the non-MCCA mesh STAs are not aware of MCCA reservations. The authors propose an improved reservation allocation vector (RAV) setup, called directional RAV (DRAV), in order to avoid the problem of ACK-induced interference, which consists of a “collision” between an ACK frame and an MCCAOP reservation. The DRAV scheme forbids a mesh STA to start an EDCA-TXOP if it crosses any MCCA reservation.

Gallardo et al. [84] propose an alternative approach to provide collision-free data transmission for the MCCA scheme, in which an RTS/CTS-based mechanism with additional control frames is used to notify the neighboring mesh STAs about the reservations, instead of using the excessive beaconing broadcast employed by the MCCA scheme. Despite the overhead reduction when compared to MCCA, this proposal does not perform any scheduling nor admission control, and the authors do not consider any interfering traffic pattern in the network.

Islam et al. [44] propose an enhanced MCCA (eMCCA) which allows MCCAOP owners to sense the channel sooner by employing a new interframe space shorter than the minimum AIFS length. It prevents non-MCCA mesh STAs from occupying the channel if they start the contention with the MCCAOP owner during a reserved MCCAOP. In addition, a preemptive channel access scheme is proposed to estimate future transmissions of MCCAOP owners. It invokes early access by the MCCAOP owner if it is predicted that transmissions from non-MCCA neighboring mesh STAs would foreshorten the MCCAOP reservation. Despite the results have shown a throughput maximization and better MCCAOP reservation usage, the preemptive access scheme is complex and may not be accurate. Its effectiveness depends largely on estimations of the channel occupancy time for the traffic type that will be transmitted by the non-MCCA neighbors of an MCCAOP owner. In the case of heterogeneous traffic types, these estimations may be inaccurate.

Another enhancement to MCCA is proposed in [85], which specifies a scheduler that reserves dimensioned and contiguous MCCAOPs for each mesh STA rather than for each flow. This scheme allows an overhead reduction and balances the voice capacity in the overall network, regardless of the number of traversed hops. However, this mechanism may prevent non-MCCA mesh STAs from transmitting at scheduled times, since their frames transmission is postponed to after contiguous MCCAOPs. If several MCCAOPs are contiguously reserved, the non-MCCA mesh STAs may experience several delays or even being prevented from transmission.

As MCCA scheme only performs reservations between adjacent mesh STAs in the neighborhood (i.e. single-hop reservations), the reservation-based HWMP (R-HWMP) has been proposed to perform end-to-end bandwidth reservation among multiple mesh STAs [51]. R-HWMP modifies the HWMP control frames by introducing some of the flow specification concepts of resource reservation protocol (RSVP). In the path discovery procedure, the R-HWMP evaluates the number of required slots by each flow transmitted from a specific source. Then, it uses the slot information to find available paths from the source to the destination. Nevertheless, this technique may also suffer from the impact of external interferences, since the required slots may be unavailable at the moment of path discovery or flows transmission.

In [132], the authors discuss the unfairness on channel access of the MCCA scheme, when dealing with bursty traffic. Since the MCCA medium access fraction (MAF) limit has a constant value, it leads to an equal-time fairness to all mesh STAs. However, due to the bursty traffic nature and the traffic load variations in the network, the mesh STAs need proportional channel access based on their traffic load. Thus, the authors propose an adaptive scheme to MCCA where each mesh STA estimates its traffic load, and, based on the required channel share, the MAF limit is adapted to reflect the network utilization and provide per-STA proportional fairness. Despite the improved fairness on channel access, the authors do not considered the existence of other traffic sources in the network.

Khorov et al. [130] propose an adaptive reservation scheme to use MCCA for streaming real-time multimedia traffic. This scheme adapts the number of MCCAOP reservations according to the estimated channel conditions (i.e. delay and packet loss ratio). It removes or adds reservations for additional transmission attempts, forming a new set of reservations, in order to reduce the interference caused by non-adjacent neighbors (i.e. two-hop distant neighbors) during the reserved periods. This scheme is able to provide support for streaming real-time multimedia traffic in the presence of interference, however the problem of neighboring block is exacerbated, since the blockage is extended to nodes which are two-hop distant, being even more restrictive than default MCCA scheme when dealing with concurrent transmissions.

As it can be drawn from the aforementioned works, most of the authors do not consider the impact of interfering traffic over the RT communication, with a relevant exception for the work presented in [130]. Moreover, the RR proposals available in the literature still present some flaws, which turn them unreliable to be used in WMNs deployed in industrial environments. In this context, the main motivation for this work is to propose and assess a new resource reservation scheme, capable of mitigating the impairments of MAC mechanisms on supporting RT communication in 802.11s-based WMNs when the wireless channel is shared with uncontrolled non-RT traffic sources.

5.4 Mesh resource reservation scheme

The Mesh Resource Reservation (MRR) is an end-to-end resource reservation scheme designed to support real-time (RT) traffic in IEEE 802.11s WMNs. It operates at MAC sublayer by reserving opportunity windows, during which the neighboring mesh STAs are compelled to contend for the channel in a slowdown contention mode. Opportunity windows are reserved in a distributed manner for all mesh STAs that belong to an RT path. Adjacent neighbors are informed about these reserved windows, and they are compelled to decrease their channel access probabilities by means of larger contention parameters. This way, the RT traffic in the RT path will benefit from channel access with less surrounding interferences, since the neighbor stations will backoff for longer.

MRR is composed of four procedures: a) reservation set-up, where opportunity windows are periodically reserved in mesh STAs; b) real-time data transmission, where messages transmission follows the MRR rules; c) reservation repair, to repair a reservation in case of change in the RT communication path; and d) reservation release, where the reservation is released when no longer needed. The next subsections present a detailed description of each procedure.

5.4.1 Reservation set-up

The reservation set-up is a process where opportunity windows are reserved in mesh STAs that are involved in the RT communication, including their adjacent neighbors. The set-up is performed before RT data transmission, where two new information elements (IEs) are defined to manage reservations: MRR reservation request (MREQ) and MRR reservation reply (MREP). These IEs are encapsulated in mesh action frames at the moment of their transmission. It is worth noting that the standard specification allows the creation of new IEs (vendor specific) [11]. Thus, the proposed IEs are standard-compliant and can be used in practical implementations of IEEE 802.11s WMNs.

Figure 5.2 presents the IEs format defined for MRR. Both IEs have the first three fields in common: the *Element ID* identifies the message type, the *Length* specifies the number of octets of the remaining element fields, and the *Window ID* specifies a unique identifier of an opportunity window. The MREQ message (Figure 5.2a) also has the *Window Start Time* field which specifies the time instant where the RT message is scheduled for transmission (t'), the *Window Duration* defines the duration of the requested opportunity window (ω), the *Window Period* is the periodicity (τ) of RT messages, and finally the *Window Offset* is an offset (ϕ) to maintain the opportunity windows synchronized across multiple hops. The MREP (Figure 5.2b), beyond the first three common fields, has yet the *Window Reply Status* field that indicates if a requested opportunity window was accepted or rejected.

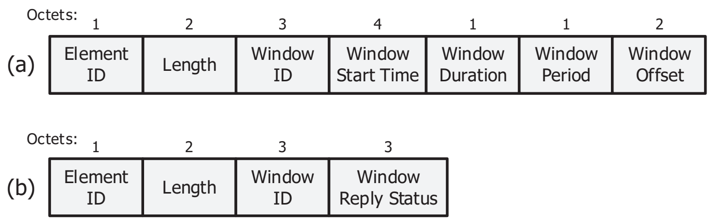

Figure 5.2 Information elements defined for MRR scheme: (a) MRR reservation request (MREQ), and (b) MRR reservation reply (MREP).

The purpose of MREQ/MREP messages is to reserve opportunity windows along a path from source to destination, and it is also used to inform the neighboring mesh STAs about the reservation. MREQ messages are originated at the source mesh STA and forwarded hop-by-hop towards the destination. As an MREQ message traverses the hops, it is also listened by the adjacent neighbors of the current hop. Upon receiving MREQ/MREP messages, each mesh STA is aware of the reservation. A reservation is only confirmed when the MREP message sent from the destination is received at the source mesh STA. If that MREP message is not received by the source mesh STA, the reservation is considered as not established and the whole process should restart. Figure 5.3 illustrates an example of a basic reservation set-up performed by mesh STAs exchanging MREQ/MREP messages.

The reservation process is initiated by the source mesh STA when the application demands the transmission of an RT message stream. The application sets the opportunity window duration (ω), the source and the destination addresses, the required periodicity (τ), the time that an RT message transmission is scheduled for transmission (t'), and an offset (ϕ). Then, the source mesh STA creates an MREQ message filling the fields with the information provided by the application and forwards it towards the destination. As the number of hops increase, the reserved opportunity window should be adjusted to start at $t' + k\times\phi$, where k is a hop counter. The hop counter value is informed to the mesh STAs through MREQ messages, which includes the number of hops traversed until reaching the current STA.

To keep control of the reservations in the network, each mesh STA keeps a local reservation table. This reservation table contains all the information of the reserved opportunity windows, as well as the RT path information in which are defined the source, next hop, and destination

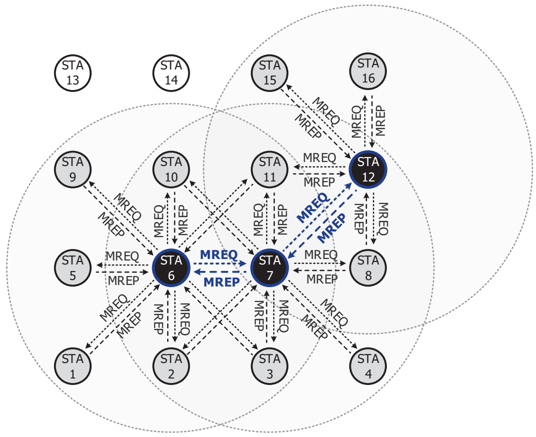

Figure 5.3 Example of MRR reservation set-up in a mesh grid topology. Mesh STAs 6, 7 and 12 are part of the RT path, where STAs 6 and 12 are the source and the destination, respectively.

addresses. During the MREQ/MREP messages exchange, before forwarding an MREQ message, a mesh STA creates an entry on its reservation table with the information provided by the MREQ message, and sets the reservation status to *requested*. Upon receiving an MREQ message, the destination mesh STA, aside from filling its reservation table, creates an MREP message, and forwards it in order to confirm the requested reservation. When an intermediate mesh STA receives an MREP message, it updates the reservation entry by changing the status to *confirmed*. Then, the mesh STA forwards the MREP message to the next hop towards the source. Once the source receives the MREP message, the reservation set-up is finished.

The path establishment is managed by the default hybrid wireless mesh protocol (HWMP). However, to establish the reservations in an end-to-end basis, the path between the source and the destination must be symmetric. To ensure this, the MREP messages are only addressed based on the reservation table information, without requesting any new routes to HWMP.

The MRR scheme also allows the reservation of multiple opportunity windows. In the case of a mesh STA transmitting multiple RT streams, the opportunity windows for each stream are allowed to overlap in the transmission schedule, as illustrated in the Figure 5.4. Contrary to DARE [52] and MCCA [11], where multiple reservations cannot overlap in the same mesh STA and are shifted in time when conflicting, MRR does allow overlapping windows, where a window can start when another one is already running, resulting in a continuous larger window.

5.4.2 Real-time data transmission

Upon reservation establishment, the RT data transmission can be initiated by the source mesh STA following the reserved opportunity windows schedule. During the channel access, mesh STAs follow the normal EDCA contention procedure.

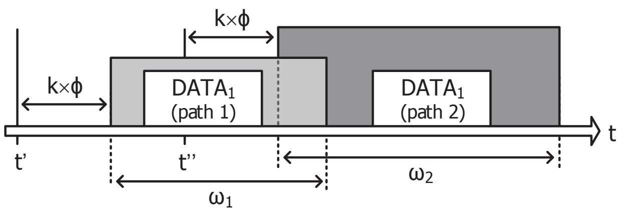

Figure 5.4 Example of two opportunity windows overlapping in a mesh STA.

An opportunity window is started according to the periodicity of the RT message stream. Upon acquiring the channel access, the RT message should be transmitted inside its opportunity window. If it misses its opportunity window, it will be prone to interferences of mesh STAs in the neighborhood. RT messages that eventually collide or miss acknowledgment during their transmission can be retransmitted as many times as defined by EDCA's retransmission attempt parameter.

Whenever an opportunity window starts, the neighboring mesh STAs will have their EDCAF contention parameter values increased, and therefore will be compelled to delay their messages transfer. Specifically, the AIFSN[AC] value is set to 15 for all ACs, based on $(2 \times N) + 1$, where N is the maximum AIFSN value defined to the background class (i.e. $N = 7$). Moreover, the contention window values are set to $aCW_{min} = 511$ and $aCW_{max} = 1{,}023$, which are the maximum CW values defined by EDCA. It is important to note that during the opportunity windows, mesh STAs implementing the MRR scheme transmit RT traffic by using the EDCA voice priority, and their contention parameters are set to the default values, differently from MCCA, in which the contention parameters of all ACs are reduced to minimum values.

During the RT data transmission, each mesh STA that is reservation-aware needs to determine the time instant when an opportunity window starts. While the RT message traverses the path towards the destination, the opportunity window start time (θ) at each hop will be adjusted in order to keep the synchronism in the subsequent mesh STAs. The neighboring mesh STAs must also determine the θ value in order to keep track of the current opportunity windows. The θ value is determined based on the transmission schedule time of an RT message (t') at the source, and it depends on the hop count (k) and the offset (ϕ) values. These values are informed by the mesh STAs that belong to the RT path during the reservation set-up phase. The θ value is given by:

$$\theta^{id}_{k+1} = t^{id} + k \times \phi \tag{5.2}$$

where id corresponds to the RT message stream identifier number, t^{id} is the time instant when a RT data transmission is scheduled to start (i.e. the timestamp that the first message should be sent by the source mesh STA). To exemplify how these parameters act during an RT message transmission, Figure 5.5 illustrates a set of reserved opportunity windows in an end-to-end communication.

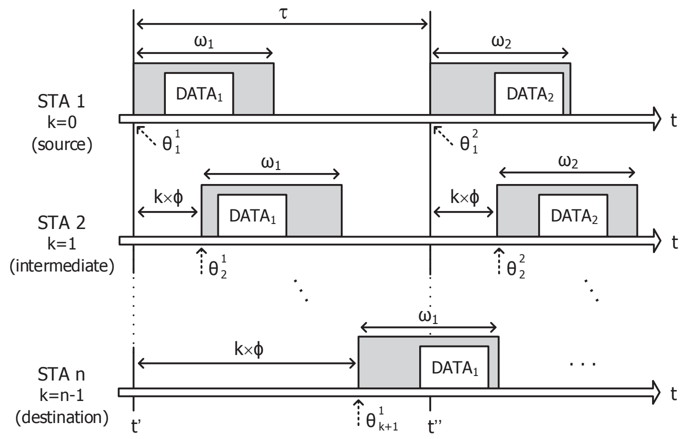

Figure 5.5 Example of RT message transmission with reserved opportunity windows across multiple hops.

According to the Figure 5.5, the opportunity window (ω_1) at the source mesh STA is started at t' (i.e. $\theta_1^1 = t'$) since the hop count is zero. Afterwards, in the mesh STA 2, the hop count is 1 and then Eq. (5.2) needs to be applied in order to adjust the opportunity window start (θ_2^1). The same principle is applied to the subsequent hops until the n^{th} mesh STA in the path (i.e. the destination), that will be synchronized with $t^{id} + (n-1) \times \phi$.

5.4.3 Reservation repair

An established reservation eventually might be broken during the RT data transmission, either by topology change or link failure. If a reservation becomes broken, a repair function must be invoked in order to reestablish the reserved opportunity windows and continue the RT data transmission. A broken reservation is detected when a mesh STA is no longer able to reach its next hop in the path, i.e., it is considered that when acknowledgments are not received after successive transmission attempts on three consecutive opportunity windows.

The reservation repair is performed in two steps: firstly, the MAC sublayer indicates a broken link and the HWMP routing protocol takes place by updating the path. After the new path establishment, the reservation table of mesh STAs involved in the RT path is updated accordingly. The reservation repair can be performed locally or globally, as described below:

- Local repair: only the mesh STAs that were involved in the broken link vicinity will update locally their reservation tables. This local repair is effective and causes low signaling on the mesh network.
- Global repair: if the reservation repair is initiated by the source mesh STA, the whole reservation will be updated.

5.4.4 Reservation release

Once a reservation is no longer needed, the MRR invokes the reservation release procedure. In order to reduce control overhead, MRR avoids to send additional control messages to release the reservations. Therefore, a timeout strategy is employed, where if a mesh STA does not receive any RT data during a defined timeout period, the reservation will be released. After releasing the reservation, the EDCAF contention values of mesh STAs are reverted back to their default values.

5.5 Issues related to the channel access in WMNs

In a previous research work [42], we assessed the communication performance of EDCA scheme to support RT traffic in an IEEE 802.11s WMN, when the channel is shared with uncontrolled non-RT traffic sources. Based on a set of simulations, it could be observed that the RT communication behavior is directly affected by the presence of non-RT traffic sources. We found that the default contention parameter values used by EDCA are not adequate to provide the required service differentiation for traffic with temporal constraints, since the EDCA scheme is not able to separate the higher priority traffic from the traffic transmitted at lower priority classes. When increasing the network utilization by non-RT traffic sources, we noticed a degradation of the performance metrics, indicating that the default parameter values should be set differently.

This problem is mainly related to the random backoff timer employed by EDCA for channel access. If two stations transmitting traffic of different priorities (i.e. at different access categories) have their backoff timer simultaneously expired, a collision occurs on channel access and a new backoff procedure is started for each station, this way delaying the channel access for the highest priority traffic (see Figure 5.6a).

The design of resource reservation mechanisms for WMNs must consider this EDCA delaying effect. Consider the example illustrated in Figure 5.6, where the medium access of two STAs is compared when using EDCA, MCCA or MRR access schemes.

For this example, consider that mesh STAs 1 and 2 are transmitting data frames at priority AC_VI and AC_VO, respectively, and that both stations are using IEEE 802.11g as PHY layer. By definition $aCW[VI]_{min} = 7$, $aCW[VO]_{min} = 5$, and AIFSN = 2. From Eq. (5.1), both stations have the same AIFS length, then they sense the channel at the same time. The backoff timer (BO) can be calculated as follows:

$$BO = \mathscr{U}(0, CW^{i}) \times aSlotTime \tag{5.3}$$

where $\mathscr{U}(0, CW^{i})$ is a uniform distribution over the interval 0 and CW^{i}, where $CW^{i} = (2 \times CW^{i-1} +$

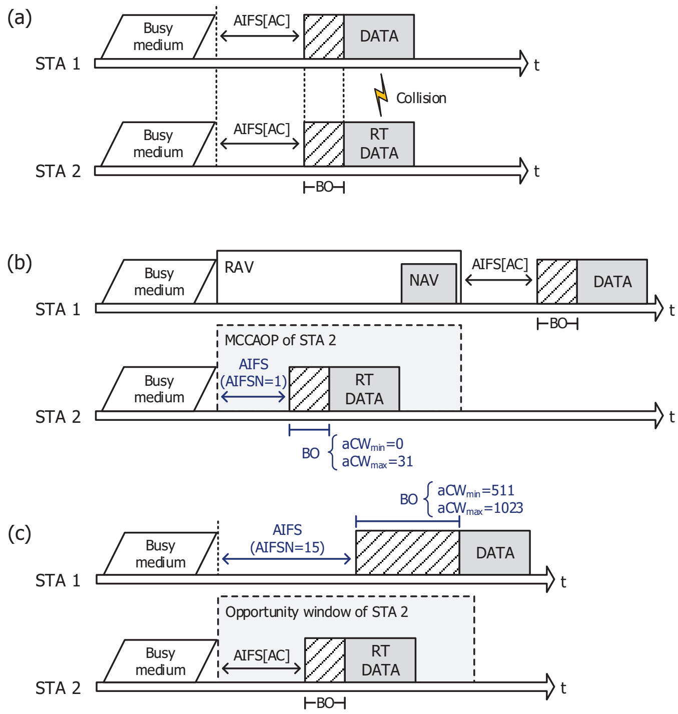

Figure 5.6 Example of medium access of two mesh STAs with (a) normal EDCA scheme, (b) MCCA scheme, and (c) MRR scheme. Mesh STA 1 is an adjacent neighbor of mesh STA 2.

1) at i^{th} backoff stage, and aSlotTime is the slot time duration defined by the PHY layer. At the initial backoff stage a value is uniformly selected from $\mathscr{U}(0,\text{aCW}_{\text{min}})$.

Suppose that both stations are in their initial BO stage, then we have $\mathscr{U}(0,7)$ for video class and $\mathscr{U}(0,5)$ for voice class. If both distributions generate the same value, the stations will have the same BO time, and when it reaches zero they will start their transmission simultaneously, causing a collision. This problem also occurs with low priority classes, however with lower probability of occurrence, since the CW size is increased at each backoff stage until reaching $\text{aCW}_{\text{max}} = 1{,}023$.

To overcome this problem, in the MCCA scheme, mesh stations that are owner of an MCCAOP have their channel contention values reduced in order to gain the channel sooner. With AIFSN = 1 and $\text{aCW}_{\text{min}} = 0$, the MCCAOP owner experiences no competition from other stations during the channel contention on a reservation. However, during an MCCAOP, the mesh STAs in the neighborhood are abstained from transmission since they set RAV/NAV timers (see Figure 5.6b). When considering the worst-case scenario, the channel access by these neighboring mesh STAs only occur after the end of the MCCAOP, and also after waiting for an AIFS[AC] period and a random backoff time. The amount of time that a station is blocked for transmission (i.e. holding time) can be denoted as follows:

$$\text{Holding time} \;=\; T_{\text{MCCAOP}} + \text{AIFS[AC]} + \text{BO} \tag{5.4}$$

where T_{MCCAOP} is the remaining time of an MCCAOP reservation.

Moreover, EDCA-TXOPs on the current MCCAOP owner are not allowed to overlap any MCCAOP reservation. The following condition should be satisfied, otherwise a random backoff is performed:

$$T_{\mathrm{DATA}} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}} < current\_time + T_{\mathrm{MCCAOP}} \tag{5.5}$$

where T_{DATA} is the transmission time of a data frame inside an EDCA-TXOP, T_{SIFS} is the aSIFSTime, and T_{ACK} is the transmission time of an acknowledge frame.

Concerning this blocking mechanism employed by MCCA scheme, it is very restrictive to the neighboring traffic. In industrial environments this is not feasible to apply, since some applications may experience communication issues due to delayed data delivery. In addition, the blocking mechanism prevents the mesh action frames from being transmitted, where it may cause unexpected delays on peer management and path selection procedures. Furthermore, if other RT streams are traversing the neighborhood of a reservation, MCCA may block their transmission to accomplish the reservation schedule, i.e., crossing reservations may block each other.

When considering the DARE scheme [52], it also employs a blocking mechanism by setting NAV timers to the stations in the neighborhood of a reservation. It is less restrictive than MCCA, once EDCA-TXOPs in the same station may overlap the reservations, and crossing reservations do not block each other. However, the problem behind the DARE scheme is related to its design, where lost RT messages are not retransmitted by any means, and also the successfully delivered messages are only acknowledged at the destination. This scheme design may lead to an increased message loss ratio, and, consequently, the RT traffic may experience more deadline misses.

The MRR scheme was proposed to mitigate the impairments that arise from the random backoff and the blocking mechanisms. During a reserved opportunity window, instead of setting RAV/NAV timers, the neighboring mesh STAs set their EDCAF contention parameters for larger values, delaying the transfer of all the neighboring traffic (slowdown contention mode). The backoff timer at the first stage of mesh STAs will follow the distribution $\mathcal{U}(0,511)$, and in the remaining stages will follow $\mathcal{U}(0,1023)$, this way reducing the probability of collisions, since the uniform distribution generates values for backoff from a wider range. With this set of EDCAF parameters, the neighboring mesh STAs gain the channel access later (see Figure 5.6c), while the mesh STAs transmitting RT traffic may benefit from the channel access with less surrounding interferences, since the network utilization during the reservations is alleviated. Moreover, seeking to mitigate the issues that arise from the blocking mechanism, a significant improvement to the MCCA scheme can be easily implemented by replacing the RAV/NAV timers by the slowdown contention mode. In the improved MCCA scheme, defined in this chapter as MCCA+MRR, the RT traffic is transmitted using the reduced channel contention values of MCCA scheme, whereas the non-RT traffic in the neighborhood follows the slowdown contention mode of MRR scheme.

5.6 Simulation model

In this section, we present a simulation assessment of several resource reservation (RR) mechanisms, specifically when those mechanisms are applied upon the MAC sublayer of IEEE 802.11s to support RT communication. The scenario of interest consists of a WMN where the RT traffic (traffic generated by high priority applications) and the non-RT traffic (interference traffic) share the same wireless channel. The target of the presented simulations is to assess how the MRR scheme is able to support RT communication when the wireless channel is subject to interference of uncontrolled traffic sources. It is also carried out a comparison among MRR and MCCA+MRR *versus* EDCA, MCCA, and DARE schemes.

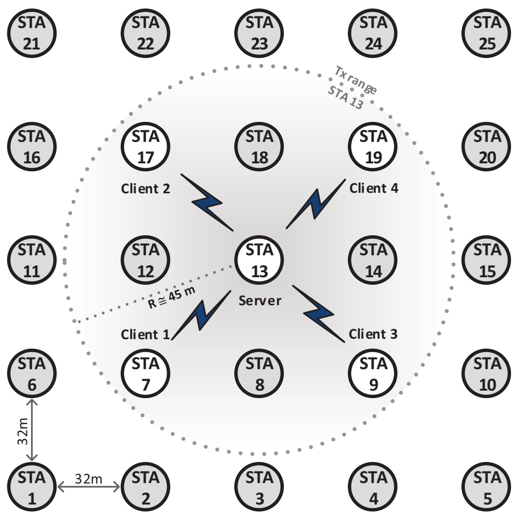

Figure 5.7 5 × 5 stationary grid topology.

A square grid topology with 25 stationary stations disposed in an area of 128 × 128 m was considered to guarantee that the network topology is well-balanced (see Figure 5.7). To avoid mesh peering instability, and to mitigate the hidden and exposed terminal problems, the antenna gains of mesh STAs were defined to reach just their adjacent neighbors. All mesh STAs were set to operate using IEEE 802.11g PHY standard, with the PHY/MAC parameter values as defined in Table 5.1.

In the simulation assessment, the number of reserved slots was varied for each RR scheme, in order to evaluate the impact of different reservation durations upon the RT communication. The offset (ϕ) value is fixed, since the RT message streams are periodic. The reservation parameters used for simulation are defined in Table 5.2. These reservation parameters are

Table 5.1 IEEE 802.11g PHY/MAC parameters.

Parameter	Description	Value
Data rate	Constant data rate (no rate adaptation)	24 Mbps
Channel number	Fixed channel number	6 (2.437 GHz)
Energy detection threshold	—	−96 dBm
Cca mode 1 threshold	Clear channel assessment threshold	−99 dBm
Antenna type	—	Omnidirectional
Tx/Rx gain	Antenna gain for transmission/reception	1.0 dBi
Tx power	Transmission power level	16.0206 dBm (40 mW)
Rx noise figure	SNR degradation in the receiver	7 dB
Propagation loss model	—	Log-distance
Error rate model	—	Nist OFDM [123]

common for the assessment of the evaluated RR schemes, except those specific for the MCCA scheme.

The MCCA scheme was modified to perform end-to-end reservations. Basically, MCCA setup requests are forwarded hop-by-hop towards the destination, following the path defined by HWMP. During the forwarding process, the neighbors along the path receive MCCAOP advertisements (MADV) in order to be informed about the opportunity windows. The schedule of MCCAOP in the first hop is similar to MCCA, where the MCCAOP start after DTIM beacon plus the offset (see Figure 5.1). However, in the following hops, the MCCAOPs are scheduled similarly to MRR, where the relation $k \times \phi$ is applied every hop (see Figure 5.5). It is important to note that MCCA offset is different from the MRR offset (ϕ). In the former, the offset is used to set the first schedule of MCCAOP in the DTIM interval, whereas the later is used to adjust the opportunity windows schedule across multiple hops in the path.

Table 5.2 Resource reservation parameters.

Parameter	Description	Value
DTIM beacon interval	Delivery traffic indication message interval	512 ms
Slot length	Duration of a reserved slot	32 µs
ω	Reservation length (in slots)	16, 32, 64 and 128
ω_{max}	Maximum ω value	128 slots (4,096 µs)
ϕ	Opportunity window offset	4 slots (128 µs)
MCCAOP offset	First MCCAOP schedule in the DTIM interval	0 slots*

* It means that the MCCAOP schedule is performed immediately after the DTIM beacon.

To perform end-to-end reservations, the path between the source and the destination of an RT message stream must be symmetric. To ensure this, upon HWMP path resolution, the path information is stored in the reservation table of mesh STAs. This way, the mesh STAs transmitting the reservation setup messages follow the path information based on their reservation table.

The simulation experiments were carried out using the network simulator 3 (ns-3), and were run in simulation batches with a duration of 400 s, being the first 200 s considered for the mesh discovery process. The path selection is performed by the HWMP in proactive mode, where a mesh STA is selected as root in order to coordinate the path selection in the network.

To assess if the RR schemes can reliably support RT traffic when the channel is shared with interfering non-RT traffic sources, we consider that at least 85% of deadlines must be met. If the ratio of deadline misses is greater than 15%, the RR scheme is considered inefficient to deal with interference traffic, and, therefore, it is not adequate for QoS provisioning for RT traffic. This threshold is called deadline miss threshold (DMT).

5.6.1 Traffic model

The simulation assessment considers four RT message streams traversing the mesh network with small fixed-sized messages of 80 and 300 bytes, and constant periodicities of 50 and 200 ms (see Table 5.3). The deadlines of RT message streams are equal to their periods. These streams are transmitted at the highest EDCA priority class *voice* and use user datagram protocol (UDP) as the transport-layer protocol.

Table 5.3 Real-time message streams definition.

Message stream #	Mesh source	Mesh destination	Message size (bytes)	Periodicity (ms)
1	STA 1	STA 25	80	50
2	STA 21	STA 5	80	200
3	STA 25	STA 1	300	200
4	STA 5	STA 21	300	50

The non-RT interference traffic was modeled to mimic a hypertext transfer protocol (HTTP) conversation. It works as a request-response protocol in the client-server computing model. Clients send requests to a server, which returns responses with the requested content. Usually, the requested content contains several objects (e.g., images, text, videos, or audio). Thus, once a server receives a request, it answers with one or multiple objects, which constitute several bursts of data.

To mimic the HTTP conversation behavior, it was considered a client side and a server side, exactly as defined in previous research work [42]. Table 5.4 summarizes the parameters used to define the HTTP traffic model, that uses the transmission control protocol (TCP) as the transport-layer protocol. To summarize the HTTP traffic model, a client sends requests varying from 10 to 2,500 bytes according to a specified periodicity (modeled by a Poisson process) and once the server receives a request, it responds after approximately 130 ms with bursts of multiple objects varying from 50 bytes to 2 Mbytes.

Table 5.4 HTTP traffic parametrization.

Parameter	Statistical characterization
Client request size	Truncated log-normal distribution: mean = 300 bytes ($\mu = 5.61$, $\sigma = 0.47$) min = 10 bytes, max = 2,500 bytes
Client request interval	Truncated Poisson process: mean = variable max = 30 s
Server response object size	Truncated log-normal distribution: mean = 7,800 bytes ($\mu = 6.17$, $\sigma = 2.36$) min = 50 bytes, max = 2 Mbytes
Number of objects per server response	Truncated Pareto distribution: mean = 5.64 min = 2 objects, max = 50 objects
Server response delay	Truncated Poisson process: mean = 130 ms ($\lambda = 7.69$) max = 250 ms

Five mesh STAs were defined to implement the HTTP traffic model, being one server and four clients. The non-RT interference traffic is set to be transmitted using multiple EDCA priority classes: 30% is transmitted using *voice*, 30% *video*, and 40% *background* classes. In order to provide an interference equally distributed across the mesh network, the interfering nodes were located at the middle of the mesh grid, as illustrated in Figure 5.7. The HTTP server is the mesh STA 13, and the HTTP clients are mesh STAs 7, 17, 9, and 19.

We defined different values for the network utilization (U) imposed by the interfering stations, specifically: 10%, 30%, and 50%. For U = 10%, the client requests are sent with a mean periodicity of 125 ms, for U = 30% with 42 ms and for U = 50% with 25 ms. These periodicity values are used as the mean value for the Poisson process that defines the client request interval.

5.6.2 Performance metrics

As performance metrics, we considered the end-to-end delay and the average ratios of deadline misses and message losses. The end-to-end delay considers the average of the sum of all the delays of each sender/receiver node pair throughout the path to destination. The delay of each node pair is the time interval between the time instant when the acknowledge frame of a message i arrives at the receiver's queue and the time instant when the message i arrives at sender's queue.

The deadline miss ratio highlights the ratio of messages that exceed their bounded delivery time, considering the difference between the time instant when a message i was received at the destination and the time instant when message i was sent from the source. If this difference between these time instants is greater than the message deadline, the message is deemed to have missed its deadline. In addition, a message that is dropped (due to exceeding its transmission attempt count or due to the queue's control algorithm) is also deemed to have exceeded its deadline.

Finally, the message loss ratio considers the messages that were effectively dropped due to transmission errors, or due to exceeding their transmission attempt count.

5.7 Simulation results

Communication scenarios have been simulated to assess the performance of the resource reservation (RR) schemes to support RT traffic in a WMN, when the wireless channel is shared with non-RT traffic. For the sake of simplicity, only the results that concern RT traffic will be presented. For all the assessed scenarios, the number of reserved slots varies from 16 to 128, as well as the network utilization by interfering traffic from 0 to 50%.

5.7.1 Assessing the impact of neighborhood blocking

The first simulation scenario concerns the assessment of the impact of neighboring blocking mechanisms upon the RT communication.

Figure 5.8 illustrates the histogram and cumulative distribution function (CDF) of end-to-end delay for the RT message stream 1 (from mesh STA 1 to mesh STA 25) when using the MCCA scheme for medium access control, with different number of reserved slots, and without any external traffic sources. RT streams 2, 3 and 4 have shown a similar behavior.

Analyzing Figure 5.8, the end-to-end delay presents distinct behaviors for different number of reserved slots. It is noticeable a higher delay and a disturbance in CDF when the number of reserved slots for an MCCAOP is increased. Clearly, the worst-case scenario is when the maximum number of slots is reserved, in which the NAV/RAV timers of the stations in the neighborhood of MCCAOPs are set for longer periods. Due to longer MCCAOPs, the RT messages that may traverse concurrently the stations in the middle of the mesh grid, may be blocked by the reservations of each other, causing this increased delay in the RT communication. Moreover, the mesh management frames transmitted in the neighborhood are also subject to the blocking, causing unexpected delays in the peering formation and routing management, which directly impacts on the RT communication performance.

It is worth noting that this communication behavior is without any interfering traffic in the network. When increasing the network utilization (U) of the interfering traffic to 10%, 30%, and 50%, the behavior of MCCA scheme is similar to the presented, but with increased

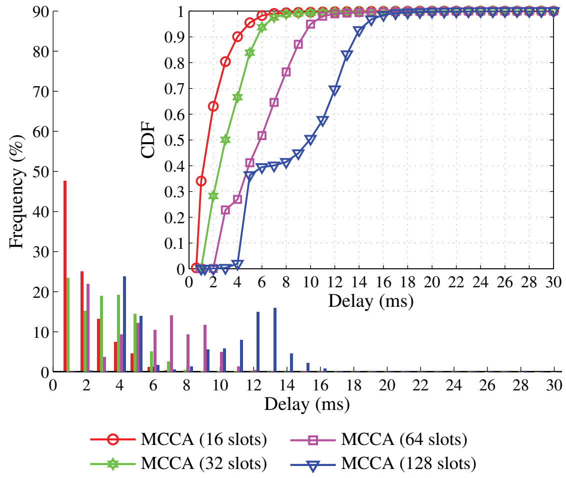

Figure 5.8 Histogram and CDF of end-to-end delay for RT message stream 1 when using MCCA scheme with different number of reserved slots.

delay values. These results indicate that the blocking mechanism of MCCA scheme is highly restrictive when longer MCCAOPs are reserved, since concurrent reservations may block each other, impacting upon RT communication performance.

Regarding the other assessed MAC mechanisms, Figure 5.9 illustrates the histogram and CDF of end-to-end delay for four RT message streams with 128 slots reserved, when subject to 50% of network utilization by interfering traffic (i.e. the worst-case scenario).

From Figure 5.9a, it is possible to notice that the blocking mechanism imposed by DARE scheme is less restrictive than of the MCCA scheme, where the histogram and CDF are less disturbed. However, DARE presents a higher delay when considering U = 50%. This result indicates that DARE scheme, in spite of not presenting blocking issues, is not efficient to deal with external traffic sources. When considering the MRR scheme, which does not employ any blocking mechanism, the end-to-end delay of RT streams is greatly reduced when compared to DARE (see Figure 5.9b). This result indicates that the slowdown contention mode imposed by MRR over the neighboring stations is quite effective to control the interferences and to reduce the end-to-end delay of RT communication.

The communication performance of MCCA+MRR is presented in the Figure 5.9c. The results present a reduction of end-to-end delay, indicating that by combining the prioritized channel access for the RT traffic and the MRR slowdown contention mode, it becomes possible to efficiently deal with external traffic sources, and consequently to improve the RT communication behavior, without blocking the transmissions in the neighborhood.

5.7.2 Assessing the effectiveness of resource reservation schemes

The second simulation scenario concerns the assessment of the effectiveness of RR schemes on QoS provisioning for the RT traffic, when dealing with uncontrolled non-RT traffic sources in

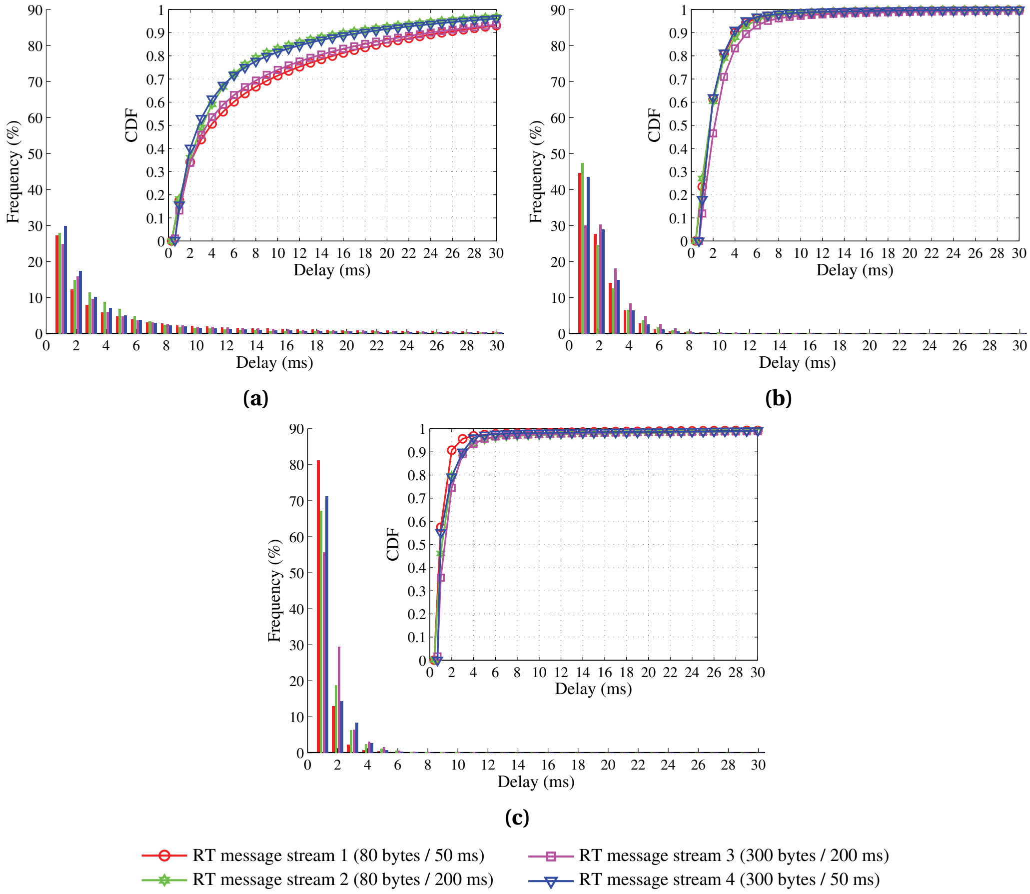

Figure 5.9 Histogram and CDF of end-to-end delay for four RT streams when using different RR schemes with 128 reserved slots and $U = 50\%$. (a) DARE, (b) MRR, and (c) MCCA+MRR.

the network. Table 5.5 presents the average end-to-end delay and the ratios of deadline misses and message losses for one RT message stream when using different RR schemes.

Analyzing the results of Table 5.5, all the RR schemes were able to effectively reduce the average end-to-end delay, and, with the exception of the DARE scheme, to reduce the ratios of deadline misses and message losses when compared to the EDCA scheme. Even when the network utilization is at 50%, a significant reduction on the metric values is observed, indicating that RR schemes are effective to deal with uncontrolled traffic sources in the WMN, and support RT communication in an end-to-end basis.

Among the evaluated RR schemes, DARE has presented the worst performance regardless of the number of reserved slots. Despite the reduced delay when compared to EDCA scheme, DARE presents a huge degradation on the ratios of deadline misses and message losses when the network utilization is above 10%. The higher number of message losses is caused by both the acknowledgment procedure at the destination node only, and by the restriction on the retransmission of lost RT messages. Moreover, above 30% of network utilization, the RT message stream presents approximately 20% of deadline misses, which is an unacceptable

Table 5.5 Communication performance of RT stream 1 when using different RR schemes and multiple reserved slots.

MAC mechanism	Network utilization (%)														
	10					30					50				
		Reserved slots					Reserved slots					Reserved slots			
		16	32	64	128		16	32	64	128		16	32	64	128
Average end-to-end delay (ms)															
EDCA	8.02	—	—	—	—	13.98	—	—	—	—	21.66	—	—	—	—
MRR	—	1.35	1.28	1.22	1.19	—	2.59	2.25	1.93	1.76	—	4.22	3.49	2.78	2.32
DARE	—	1.78	1.74	1.75	1.73	—	4.91	4.84	4.86	4.76	—	9.20	9.01	8.99	8.85
MCCA	—	1.32	2.21	3.93	7.11	—	1.32	2.24	4.01	7.25	—	1.35	2.27	4.07	7.40
MCCA+MRR	—	1.81	1.65	1.69	1.65	—	2.67	2.15	1.76	1.69	—	3.80	2.76	1.87	1.74
Deadline miss ratio (%)															
EDCA	12.69	—	—	—	—	17.48	—	—	—	—	20.97	—	—	—	—
MRR	—	1.65	1.91	1.79	1.82	—	3.59	3.63	3.80	3.95	—	5.42	5.53	5.75	5.70
DARE	—	7.54	8.12	6.96	7.02	—	19.69	18.66	19.39	19.04	—	29.50	28.19	28.17	26.80
MCCA	—	1.36	1.31	1.80	2.39	—	1.43	1.31	1.86	2.44	—	1.68	1.46	2.12	2.55
MCCA+MRR	—	3.55	3.27	3.57	3.59	—	6.65	6.90	4.94	4.20	—	8.54	9.14	5.87	4.46
Message loss ratio (%)															
EDCA	9.89	—	—	—	—	11.63	—	—	—	—	12.82	—	—	—	—
MRR	—	1.64	1.90	1.79	1.82	—	3.50	3.56	3.76	3.93	—	5.09	5.31	5.61	5.63
DARE	—	7.51	8.09	6.94	7.00	—	19.45	18.42	19.17	18.82	—	28.67	27.40	27.39	26.05
MCCA	—	1.36	1.31	1.80	2.38	—	1.43	1.31	1.86	2.42	—	1.68	1.46	2.12	2.55
MCCA+MRR	—	3.13	2.83	3.07	3.06	—	6.31	6.51	4.50	3.71	—	8.12	8.72	5.56	4.18

value when considering RT applications in industrial environments.

Regarding the MCCA scheme, distinct behaviors can be observed when considering the minimum and the maximum number of reserved slots. As indicated in the previous scenario, the end-to-end delay of RT streams increases when the number of reserved slots is increased. This problem is related to the blocking mechanism, which blocks the concurrent RT transmissions in the neighborhood. On the other hand, when the number of reserved slots is decreased to the minimum, the RT communication is greatly improved, since the problem of blocking concurrent RT transmissions is minimized with shorter MCCAOPs.

Moreover, the MCCA scheme excels by presenting almost constant metric values when a fixed number of reserved slots is considered, regardless of the network utilization imposed by the interfering traffic. Due to the blocking mechanism in the neighborhood and the prioritized channel access, in which the channel contention values are minimum, the stations transmitting RT messages experience no competition from other stations during a reservation, since they are able to gain access to the channel sooner. Thus, the RT communication presents constant metric values. These results indicate that MCCA scheme efficiently deals with uncontrolled traffic sources in the network, when shorter MCCAOPs are reserved.

MRR and MCCA+MRR schemes also significantly reduce the end-to-end delay for the RT streams. Both schemes present an improved performance when the maximum number of slots is reserved. Longer reservation durations induce the slowdown contention mode of neighboring stations for longer, thus minimizing the impact of non-RT traffic transmission upon RT communication. However, when the network utilization is increased, both schemes present a slightly degradation on the ratios of deadline misses and messages losses. As if no blocking mechanism is used, it is expected some disturbance in the RT communication performance.

Despite the slightly worst performance when compared to MCCA, the MRR and MCCA+MRR schemes efficiently control the external traffic sources without employing any blocking mechanism over the neighboring transmissions. These results indicate that the slowdown contention mode is an efficient alternative to the blocking mechanism of MCCA scheme.

5.7.3 Assessing the effectiveness of resource reservation schemes across multiple hops

A final simulation scenario concerns the assessment of the effectiveness of RR schemes when the number of traversed hops in the path is increased. For this specific assessment, to assess the communication performance with no concurrent RT transmissions, we considered only one RT stream traversing the network, specifically the RT stream 1 (see Table 5.3). Moreover, the mesh STAs belonging to the path are traversed by the RT stream only once, i.e., any mesh STA is repeated/revisited in the path.

Figure 5.10 illustrates the communication performance of one RT message stream when traversing multiple hops with a network utilization of 50%. The number of hops was varied from 4 to 16 in steps of 4. To ensure that the RT streams traverses exactly the defined number of hops, a fixed path was specified in the HWMP routing table of each station.

Commonly, when the number of hops is increased, the performance metric values worsen. When analyzing the behavior of the RR schemes regarding the number of traversed hops, this common behavior is no exception.

Regarding the MCCA scheme, when the number of traversed hops is greater than 8, the performance metric values present a sharp degradation, regardless of the number of reserved slots. Despite not having any concurrent RT transmissions, this behavior is justified, once again, by the blocking mechanism, which restricts the transmission of mesh management frames in the neighborhood of MCCAOPs. Since the mesh grid in this assessment has 25 nodes, when the RT message stream traverses 10 or more hops (without repetition), a considerable portion of the grid is blocked by the reservations, causing disturbances in the mesh peering formation and routing management, and consequently increasing the delay and the ratios of deadline misses and message losses. However, despite the degradation on metrics, the MCCA scheme when reserving shorter MCCAOPs is still able to keep the deadline miss ratio below the defined DMT value of 15%.

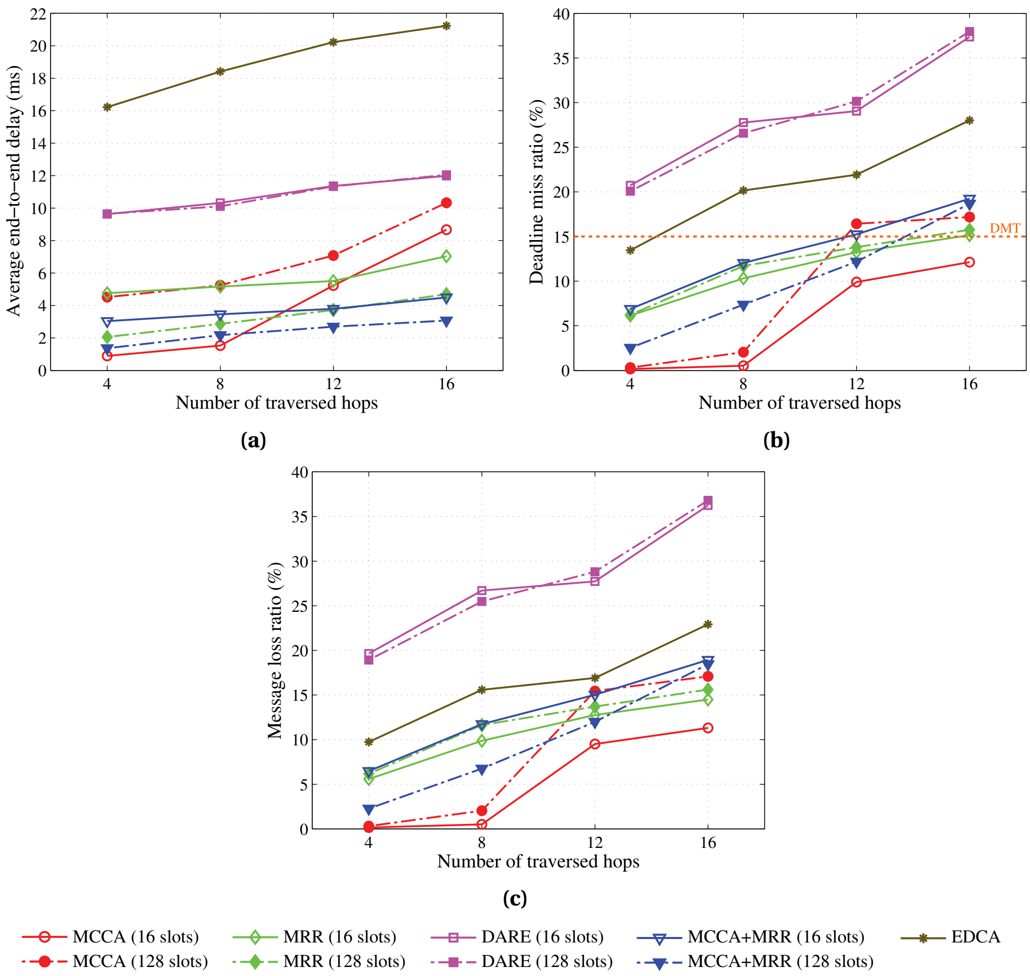

Figure 5.10 Communication performance of one RT message stream across multiple hops when using different RR schemes with $U = 50\%$. (a) Average end-to-end delay, (b) deadline miss ratio, and (c) message loss ratio.

The MRR and MCCA+MRR schemes provide a relatively low and almost constant end-to-end delay as the number of traversed hops increases. However, when the number of hops is above 12, the DMT value is exceeded, indicating that both schemes present some degradation on the ratios of deadline misses and messages losses with higher number of traversed hops.

The DARE scheme, due to the problems previously discussed regarding the restriction on lost messages retransmission, and the acknowledgment at the destination only, presents a remarkable degradation on the performance metrics when the number of hops increases, which turns the scheme unsuitable to support RT traffic in the WMNs.

These results indicate that the RR schemes are efficient to provide QoS guarantees to the RT traffic while dealing with uncontrolled traffic sources, only when the number of hops in the path is below 12. In addition, the RT communication benefits from the usage of the slowdown contention mode, instead of blocking the stations in the neighborhood.

5.8 Conclusions

This chapter proposes a new resource reservation (RR) scheme, called Mesh Resource Reservation (MRR), proposed as an end-to-end reservation scheme targeting the RT communication support in IEEE 802.11s WMNs. The objective of the proposed scheme is to provide QoS guarantees to the RT traffic when the wireless channel is shared with uncontrolled traffic sources. For this purpose, the MRR scheme reserves time intervals in the stations belonging to an RT path, during which the neighboring stations contend for the channel in a slowdown contention mode. A set of simulation results demonstrates that the RT communication benefits from the usage of RR schemes, where the performance metrics were greatly improved. However, some relevant impairments which limit the effectiveness of MCCA and DARE schemes on QoS provisioning were also identified. Despite the improved communication performance when using the MCCA scheme in end-to-end communication, it presents some issues when dealing with concurrent RT message streams transmission. Due to its blocking mechanism, concurrent reservations may block the transmission of each other, causing unpredictable delays and consequently disturbing the overall RT communication. Regarding the DARE scheme, it restricts the retransmission of lost RT messages which leads to increased ratios of message losses and deadline misses, by turning it inefficient to deal with uncontrolled traffic sources in the network.

Due to these impairments, the MRR scheme takes place by employing the slowdown contention mode to deal with uncontrolled traffic sources which does not restrict the non-RT communication in the neighborhood. The slowdown contention mode relies on increased channel contention values, which retard the channel access by non-RT traffic transmissions. Despite presenting slightly worse metric values when compared to MCCA, the MRR scheme was efficient to reduce the end-to-end delay and the ratios of message losses and deadline misses of the RT communication, even considering concurrent reservations.

Considering the effectiveness of the MRR scheme in dealing with non-RT traffic interferences, and to mitigate the MCCA impairments that arise from its blocking mechanism, we devised and assessed an improved MCCA scheme, named as MCCA+MRR, which combines the prioritized channel access of MCCA and the slowdown contention mode of MRR. The results demonstrate that this combination of schemes is efficient to deal with uncontrolled traffic sources, since the performance metrics of RT communication were also improved.

This assessment indicates that RR schemes which rely on blocking mechanisms are restrictive and should not be used to support RT communication in 802.11s WMNs. This way, we suggest to apply the slowdown contention mode as an efficient scheme to deal with uncontrolled traffic sources while providing QoS guarantees to the RT communication.

CHAPTER 6

Conclusions and future work

This chapter presents the final considerations regarding the research results achieved in this work, highlighting how the contributions have fulfilled the original research objectives. Moreover, some research directions that may emerge from this work are presented.

6.1 Conclusions

The major motivation for the research work presented in this thesis was to propose efficient schemes targeting the support of real-time (RT) communication in IEEE 802.11s wireless mesh networks (WMNs). Within this context, several approaches to support RT communication have been presented, with special emphasis to QoS solutions for 802.11-based WMNs. The main focus of this research work was the design and assessment of communication solutions intended to support RT communication in shared wireless mesh environments.

Initially, a study of the state-of-the-art on QoS provisioning and RT communication support in 802.11-based WMNs has been done. The literature related to the topic has been reviewed, seeking to identify the current QoS solutions, as well as the main challenges, impairments and requirements. As key challenges and impairments, we have identified that, beyond the unreliability of wireless channels, the multi-hop communication exacerbate some impairments, such as: a) the hidden and exposed terminal problems; b) throughput degradation across multiple hops; c) instability of wireless links; and d) the lack of a centralized channel access control. We have found out that most of these impairments are caused by the inability of medium access control (MAC) mechanisms to provide fairness in channel access in multi-hop communication scenarios.

In this sense, seeking to complement and verify these findings, we have assessed the behavior of the enhanced distributed channel access (EDCA) scheme, which is the default MAC mechanism of 802.11s WMN standard, regarding its capacity to support real-time communication. We have demonstrated, by extensive simulation experiments using network simulator 3 (ns-3), that the EDCA mechanism is not able to provide the adequate service differentiation for RT traffic when the wireless medium is shared with uncontrolled non-RT traffic sources. The non-RT traffic severely impacts on the real-time communication performance. The non-deterministic backoff mechanism employed by EDCA leads to unpredictable channel access delays, and also to the priority inversion issue, where the traffic transmitted at high-priority queues may have longer backoff timer than that transmitted at low-priority queues, consequently may access the channel later. Since the RT traffic has specific service requirements, such as strict transmission deadlines, this priority inversion issue impairs the provision of QoS guarantees for time-constrained traffic.

This way, to support real-time communication in WMNs it is necessary to provide additional means to improve the MAC mechanisms, aiming to surpass these impairments. For this purpose, the EDCA MAC mechanism should be improved by robust QoS solutions, such as resource reservation, admission and congestion control, rate adaptation and multi-channel capability. Among them, we have pointed out that the most promising QoS solution to support RT communication is the reservation of dedicated resources for time-constrained traffic.

Within this context, we have proposed the mesh resource reservation (MRR) scheme to improve the EDCA MAC mechanism with resource reservation capabilities in order to provide end-to-end QoS guarantees for real-time traffic in 802.11s WMNs. The MRR scheme reserves time intervals during which the neighboring stations of a real-time path are compelled to contend for the channel in a slowdown contention mode. Through several simulation experiments, we assessed the performance of MRR scheme, and the results have shown that the slowdown contention mode is able to reduce the surrounding interferences over the real-time traffic, and therefore is able to improve the overall communication performance. Moreover, we have compared the performance of the MRR scheme with MCF controlled channel access (MCCA) and distributed end-to-end allocation of time slots for real-time (DARE) resource reservation schemes. We have demonstrated that, despite improving the communication performance by means of time slots reservation, the blocking scheme employed by both schemes upon transmissions in the neighboring stations of an RT path is very restrictive, and impact on concurrent RT streams transmission. This way, we have proved that the slowdown contention mode is an efficient solution to deal with uncontrolled non-RT traffic sources, without disturbing the RT communication.

Thus, we conclude that resource reservations help to maintain the required upper bounds for delay, jitter, and ratios of frame losses and deadline misses for RT traffic. Moreover, resource reservation schemes are able to mitigate the unpredictable channel access delays, to reduce the collision probability, and also to provide fairness in channel usage. Therefore, we stated that the support of RT communication in 802.11s WMNs is possible using resource reservation schemes, such as the proposed MRR scheme.

6.2 Future directions for research work

Within the context of this thesis work, it is of our belief that there are many future research directions to achieve real-time communication support in wireless mesh networks. In the following paragraphs we describe two possible research directions that might be explored.

A performance analysis of the IEEE 802.11aa and 802.11ae schemes applied to the context of WMNs seems to be an interesting approach to improve the RT communication, and also to mitigate some of the current MAC mechanisms impairments. The 802.11aa scheme was proposed to improve the QoS provisioning for robust audio–video streaming, while the 802.11ae was proposed to provide specific service differentiation for control frames.

As another potential research direction, we suggest an approach which may combine multiple QoS provisioning techniques targeting the support of time-constrained traffic in WMNs. Since a unique QoS solution, by itself, is not able to fully satisfy all the QoS requirements of RT traffic, and also to mitigate its current impairments, a combination of multiple QoS solutions coupled with each other by means of an architecture seems a promising approach. In this sense, Figure 6.1 presents the logical blocks of the potential architecture.

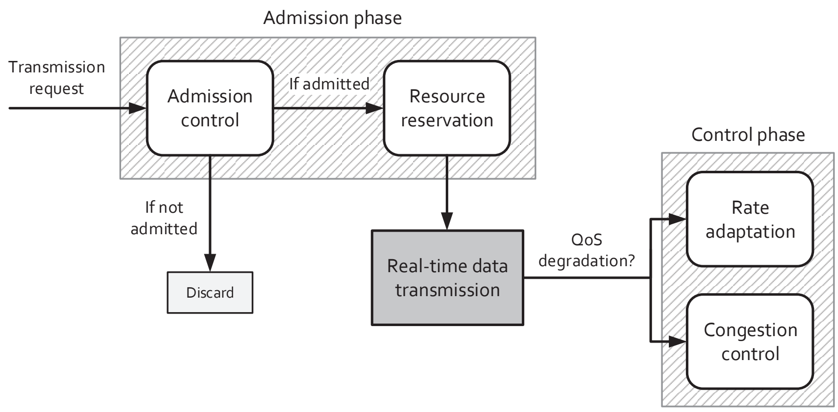

Figure 6.1 Potential architecture with robust QoS solutions for real-time communication support.

Basically, the architecture may be comprised of two distinct phases: one for traffic admission and other for traffic control. In the admission phase, the admission control and resource reservation schemes are responsible to control the traffic admission under specific requirements, and to reserve resources according to their availability in the network. Meanwhile, the control phase may only takes place when real-time communication experiences some degradation of QoS metrics. This way, rate adaptation and congestion control schemes may be applied in order to mitigate this metrics degradation.

Endnotes

[a] Adapted from Figure 1 at [5].
[b] Adapted from Slide 57 at <http://www.ieee802.org/802_tutorials/06-November/802.11s_Tutorial_r5.pdf>.
[c] Adapted from Figure 2 at [5].
[d] Adapted from Figure 9-1 at [11].
[e] Adapted from Figure 9-4 at [11].
[f] Adapted from Figure 9-19 at [11].
[g] Adapted from Figure 9-3 at [11].
[h] Adapted from Figure 9-24 at [11].
[i] Adapted from Figure 3 at [44].
[j] The initial draft version of IEEE 802.11s specified the MCCA as mesh deterministic access (MDA). However, this nomenclature was deprecated in the final amendment to the standard. The proposal by Ali et al. [85] was based on that deprecated nomenclature, but for simplicity, we used the new nomenclature instead of that used by the authors.

References

[1] S. Dhawan. Analogy of Promising Wireless Technologies on Different Frequencies: Bluetooth, WiFi, and WiMAX. In *2nd International Conference on Wireless Broadband and Ultra Wideband Communications (AusWireless'2007)*, 9 p., Sydney, NSW, AU, Aug. 2007. DOI:10.1109/AUSWIRELESS.2007.27 [Cited on p. 1]

[2] D. Goodman. The wireless Internet: promises and challenges. *IEEE Computer*, 33(7): 36–41, July 2000. DOI:10.1109/2.869368 [Cited on p. 1]

[3] A. Willig. Recent and Emerging Topics in Wireless Industrial Communications: A Selection. *IEEE Transactions on Industrial Informatics*, 4(2):102–124, May 2008. DOI:10.1109/TII.2008.923194 [Cited on p. 1, 2]

[4] X. Wang, A. Lim. IEEE 802.11s wireless mesh networks: Framework and challenges. *Ad Hoc Networks*, 6(6):970–984, 2008. DOI:10.1016/j.adhoc.2007.09.003 [Cited on p. 1, 69]

[5] G. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona et al. IEEE 802.11s: The WLAN Mesh Standard. *IEEE Wireless Communications*, 17(1):104–111, Feb. 2010. DOI:10.1109/MWC.2010.5416357 [Cited on p. 1, 15, 16, 98]

[6] D. Tardioli, D. Sicignano, J. L. Villarroel. A wireless multi-hop protocol for real-time applications. *Computer Communications*, 55:4–21, Jan. 2015. DOI:10.1016/j.comcom.2014.08.012 [Cited on p. 1, 68]

[7] M. Conti, S. Giordano. Multihop Ad Hoc Networking: The Theory. *IEEE Communications Magazine*, 45(4):78–86, Apr. 2007. DOI:10.1109/MCOM.2007.343616 [Cited on p. 1]

[8] R. Carrano, D. Saade, M. Campista, I. Moraes, C. Albuquerque et al. Multihop MAC: IEEE 802.11s Wireless Mesh Networks. In D. P. Agrawal, X. Bin (Eds.), *Encyclopedia on Ad Hoc and Ubiquitous Computing: Theory and Design of Wireless Ad hoc, Sensor, and Mesh Networks*, ch. 19, pp. 501–531. World Scientific Publishing Co., River Edge, NJ, USA, 2009. DOI:10.1142/9789812833495_0019 [Cited on p. 2, 31]

[9] I. F. Akyildiz, X. Wang, W. Wang. Wireless Mesh Networks: a Survey. *Computer Networks*, 47:445–487, Mar. 2005. DOI:10.1016/j.comnet.2004.12.001 [Cited on p. 2, 31, 44, 68]

[10] R. Carrano, L. Magalhães, D. Saade, C. Albuquerque. IEEE 802.11s Multihop MAC: A Tutorial. *IEEE Communications Surveys & Tutorials*, 13(1):52–67, Feb. 2011. DOI:10.1109/SURV.2011.040210.00037 [Cited on p. 2, 15, 18, 44, 68]

[11] IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pp. 1–2793, 2012. DOI:10.1109/IEEESTD.2012.6178212 [Cited on p. 2, 22, 24, 26, 27, 44, 45, 47, 56, 68, 69, 70, 76, 78, 98]

[12] R. Moraes, F. Vasques, P. Portugal, J. Fonseca. VTP-CSMA: A Virtual Token Passing Approach for Real-Time Communication in IEEE 802.11 Wireless Networks. *IEEE Transactions on Industrial Informatics*, 3(3):215–224, Aug. 2007. DOI:10.1109/TII.2007.903224 [Cited on p. 2, 69]

[13] J.-M. Farines, J. S. Fraga, R. S. de Oliveira. *Sistemas de Tempo Real*. Departamento de Automação e Sistemas – Universidade Federal de Santa Catarina, Florianópolis, SC, Brasil, 2000. [Cited on p. 2]

[14] Real-Time Traffic over WLAN Quality of Service. In *Real-Time Traffic over Wireless LAN Solution Reference Network Design Guide*, ch. 3, pp. 47–77. Cisco Systems Inc., Nov. 2013. Available at: http://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Mobility/RToWLAN/CCVP_BK_R7805F20_00_rtowlan-srnd.pdf [Accessed 05 April 2015]. [Cited on p. 3]

[15] IEEE Standard for Local and Metropolitan Area Networks: Media Access Control (MAC) Bridges. *IEEE Std 802.1D-2004 (Revision of IEEE Std 802.1D-1998)*, pp. 1–277, June 2004. DOI:10.1109/IEEESTD.2004.94569 [Cited on p. 3, 25, 46]

[16] W. Stallings. LAN QoS. *The Internet Protocol Journal*, 4(1):16–23, Mar. 2001. [Cited on p. 3, 25]

[17] S. Marwaha, J. Indulska, M. Portmann. Challenges and recent advances in QoS provisioning in wireless mesh networks. In *8th IEEE International Conference on Computer and Information Technology (CIT'2008)*, pp. 618–623, July 2008. DOI:10.1109/CIT.2008.4594746 [Cited on p. 3]

[18] X. Yu, P. Navaratnam, K. Moessner. Resource Reservation Schemes for IEEE 802.11-Based Wireless Networks: A Survey. *IEEE Communications Surveys Tutorials*, 15(3):1042–1061, July 2013. DOI:10.1109/SURV.2012.111412.00029 [Cited on p. 3, 8, 33, 41]

[19] M. Natkaniec, K. Kosek-Szott, S. Szott, G. Bianchi. A Survey of Medium Access Mechanisms for Providing QoS in Ad-Hoc Networks. *IEEE Communications Surveys Tutorials*, 15(2):592–620, May 2013. DOI:10.1109/SURV.2012.060912.00004 [Cited on p. 3, 68]

[20] E. S. Aguiar, B. A. Pinheiro, J. F. Figueirêdo, E. Cerqueira, A. J. Abelém et al. Trends and Challenges for Quality of Service and Quality of Experience for Wireless Mesh Networks. In N. Funabiki (Ed.), *Wireless Mesh Networks*, ch. 6, pp. 127–148. InTech, 2011. DOI:10.5772/13699 [Cited on p. 3]

[21] N. Nandiraju, D. Nandiraju, L. Santhanam, B. He, J. Wang et al. Wireless Mesh Networks: Current Challenges and Future Directions of Web-In-The-Sky. *IEEE Wireless Communications*, 14(4):79–89, Aug. 2007. DOI:10.1109/MWC.2007.4300987 [Cited on p. 3]

[22] P. Cardieri. Modeling Interference in Wireless Ad Hoc Networks. *IEEE Communications Surveys & Tutorials*, 12(4):551–572, May 2010. DOI:10.1109/SURV.2010.032710.00096 [Cited on p. 3]

[23] L. Wang, K. Wu, M. Hamdi. Combating Hidden and Exposed Terminal Problems in Wireless Networks. *IEEE Transactions on Wireless Communications*, 11(11):4204–4213, Nov. 2012. DOI:10.1109/TWC.2012.092712.120628 [Cited on p. 4, 68]

[24] G. M. Zhu, G. S. Kuo. A Fast Forward Medium Access Control Protocol for IEEE 802.11s Mesh Networks with Multiple Channels. In *IEEE Sarnoff Symposium'2007*, pp. 1–6, Princeton, NJ, USA, 2007. DOI:10.1109/SARNOF.2007.4567399 [Cited on p. 4, 7, 8, 38, 41]

[25] S. Jha, M. Hassan. *Engineering Internet QoS*. Artech House, 2002. [Cited on p. 5, 6, 32, 33]

[26] R. Braden, D. Clark, S. Shenker. Integrated Services in the Internet Architecture: an Overview [Online]. Request for Comments (RFC) 1633, Internet Engineering Task Force, June 1994. Available at: http://www.rfc-editor.org/rfc/rfc1633.txt [Accessed 20 May 2014]. [Cited on p. 5, 32, 73]

[27] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang et al. An Architecture for Differentiated Services [Online]. Request for Comments (RFC) 2475, Internet Engineering Task Force, Dec. 1998. Available at: http://www.rfc-editor.org/rfc/rfc2475.txt [Accessed 20 May 2014]. [Cited on p. 5, 73]

[28] DiffServ – The Scalable End-to-End QoS Model [Online]. Tech. rep., Cisco Systems, Aug. 2005. Available at: http://www.cisco.com/en/US/technologies/tk543/tk766/technologies_white_paper09186a00800a3e2f.pdf [Accessed 05 April 2015]. [Cited on p. 5]

[29] J. Hui, M. Devetsikiotis. A Unified Model for the Performance Analysis of IEEE 802.11e EDCA. *IEEE Transactions on Communications*, 53(9):1498–1510, Sept. 2005. DOI:10.1109/TCOMM.2005.855013 [Cited on p. 6, 48]

[30] Z.-N. Kong, D. Tsang, B. Bensaou, D. Gao. Performance analysis of IEEE 802.11e contention-based channel access. *IEEE Journal on Selected Areas in Communications*, 22(10):2095–2106, Dec. 2004. DOI:10.1109/JSAC.2004.836019 [Cited on p. 6, 48]

[31] Y. Xiao. Performance Analysis of priority schemes for IEEE 802.11 and IEEE 802.11e wireless LANs. *IEEE Transactions on Wireless Communications*, 4(4):1506–1515, July 2005. DOI:10.1109/TWC.2005.850328 [Cited on p. 6, 48]

[32] Z. Tao, S. Panwar. Throughput and delay analysis for the IEEE 802.11e enhanced distributed channel access. *IEEE Transactions on Communications*, 54(4):596–603, Apr. 2006. DOI:10.1109/TCOMM.2006.873066 [Cited on p. 6, 48]

[33] L. Xiong, G. Mao. Saturated Throughput Analysis of IEEE 802.11e EDCA. *Computer Networks*, 51(11):3047–3068, 2007. DOI:10.1016/j.comnet.2007.01.002 [Cited on p. 6, 48]

[34] E. Karamad, F. Ashtiani. Performance analysis of IEEE 802.11 DCF and 802.11e EDCA based on queueing networks. *IET Communications*, 3(5):871–881, May 2009. DOI:10.1049/iet-com.2008.0676 [Cited on p. 6, 48]

[35] M. El Masri, S. Abdellatif. Managing the virtual collision in IEEE 802.11e EDCA. In *8th IFAC International Conference on Fieldbuses and Networks in Industrial and Embedded Systems*, 1, pp. 104–109, May 2009. DOI:10.3182/20090520-3-KR-3006.00016 [Cited on p. 6, 48]

[36] Y. He, J. Sun, X. Ma, A. V. Vasilakos, R. Yuan et al. Semi-Random Backoff: Towards Resource Reservation for Channel Access in Wireless LANs. *IEEE/ACM Transactions on Networking*, 21(1):204–217, Feb. 2013. DOI:10.1109/TNET.2012.2202323 [Cited on p. 6, 48]

[37] T. Sanguankotchakorn, A. Gopalasingham, N. Sugino. Adaptive Channel Access Mechanism for Real Time Traffic over IEEE 802.11e Wi-Fi Network. In *4th International Conference on Intelligent Systems Modelling Simulation (ISMS'2013)*, pp. 486–491, Jan. 2013. DOI:10.1109/ISMS.2013.80 [Cited on p. 6, 48]

[38] F. Ning, Y. Wang. A New Adaptive EDCA Scheme for Improving the Performance of IEEE 802.11s Network. In *Spring Congress on Engineering and Technology (S-CET'2012)*, pp. 1–4, May 2012. DOI:10.1109/SCET.2012.6342138 [Cited on p. 6]

[39] R. Achary, V. Vaithiyanathan, P. Raj, S. Nagarajan. Performance enhancement of IEEE 802.11e WLAN by dynamic adaptive contention window. In *16th International Conference on Advanced Communication Technology (ICACT'2014)*, pp. 447–452, Feb. 2014. DOI:10.1109/ICACT.2014.6779000 [Cited on p. 6]

[40] C. M. D. Viegas, S. Sampaio, F. Vasques, P. Portugal, P. Souto. Assessment of the Interference Caused by Uncontrolled Traffic Sources upon Real-Time Communication in IEEE 802.11-based Mesh Networks. In *9th IEEE International Workshop on Factory Communication Systems (WFCS'2012)*, pp. 59–62, Lemgo, Germany, May 2012. DOI:10.1109/WFCS.2012.6242541 [Cited on p. 6, 11, 45]

[41] C. M. D. Viegas, F. Vasques, P. Portugal. Evaluating the impact of uncontrolled traffic sources upon real-time communication in IEEE 802.11s mesh networks. In *12th IEEE International Conference on Industrial Informatics (INDIN'2014)*, pp. 106–111, Porto Alegre, RS, Brazil, July 2014. DOI:10.1109/INDIN.2014.6945492 [Cited on p. 6, 11]

[42] C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources. *EURASIP Journal on Wireless Communications and Networking*, 2014(219):1–15, 2014. DOI:10.1186/1687-1499-2014-219 [Cited on p. 6, 11, 12, 68, 69, 81, 86]

[43] A. Krasilov, A. Lyakhov, A. Safonov. Interference, Even with MCCA Channel Access Method in IEEE 802.11s Mesh Networks. In *8th IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS'2011)*, pp. 752–757, Valencia, Spain, Oct. 2011. DOI:10.1109/MASS.2011.83 [Cited on p. 6, 35, 44, 50, 68, 74]

[44] M. Islam, M. Alam, C. S. Hong, S. Lee. eMCCA: An enhanced mesh coordinated channel access mechanism for IEEE 802.11s wireless mesh networks. *Journal of Communications and Networks*, 13(6):639–654, Dec. 2011. DOI:10.1109/JCN.2011.6157481 [Cited on p. 6, 74, 98]

[45] IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks – Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications – Amendment 1: Prioritization of Management Frames [Online]. *IEEE Std 802.11ae-2012 (Amendment to IEEE Std 802.11-2012)*, pp. 1–52, 2012. Available at: http://standards.ieee.org/about/get/802/802.11.html [Accessed 05 March 2015]. [Cited on p. 6]

[46] IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks – Specific

requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications – Amendment 2: MAC Enhancements for Robust Audio Video Streaming [Online]. *IEEE Std 802.11aa-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012)*, pp. 1–162, 2012. Available at: http://standards.ieee.org/about/get/802/802.11.html [Accessed 05 March 2015]. [Cited on p. 6]

[47] A. Banchs, A. De La Oliva, L. Eznarriaga, D. Kowalski, P. Serrano. Performance Analysis and Algorithm Selection for Reliable Multicast in IEEE 802.11aa Wireless LAN. *IEEE Transactions on Vehicular Technology*, 63(8):3875–3891, Oct. 2014. DOI:10.1109/TVT.2014.2306014 [Cited on p. 7]

[48] A. Hamidian, U. Körner. Providing QoS in Ad Hoc Networks with Distributed Resource Reservation. In *Managing Traffic Performance in Converged Networks*, vol. 4516 of *Lecture Notes in Computer Science (Springer)*, pp. 309–320. 2007. DOI:10.1007/978-3-540-72990-7_30 [Cited on p. 7, 34]

[49] G. Hiertz, J. Habetha, P. May, E. Weib, R. Bagul, S. Mangold. A Decentralized Reservation Scheme for IEEE 802.11 Ad Hoc Networks. In *Proceedings of 14th IEEE on Personal, Indoor and Mobile Radio Communications (PIMRC'2003)*, vol. 3, pp. 2576–2580, Sept. 2003. DOI:10.1109/PIMRC.2003.1259192 [Cited on p. 7, 44, 49, 69, 73]

[50] J. Ben-othman, L. Mokdad, M. Cheikh. Q-HWMP: Improving End-to-End QoS for 802.11s Based Mesh Networks. In *IEEE Global Telecommunications Conference (GLOBECOM'2010)*, pp. 1–6, Dec. 2010. DOI:10.1109/GLOCOM.2010.5683584 [Cited on p. 7]

[51] W. J. Jung, S. H. Min, B. G. Kim, H. S. Choi, J. Y. Lee, B. C. Kim. R-HWMP: Reservation-based HWMP supporting end-to-end QoS in Wireless Mesh Networks. In *International Conference on Information Networking (ICOIN'2013)*, pp. 385–390, Jan. 2013. DOI:10.1109/ICOIN.2013.6496409 [Cited on p. 7, 44, 50, 69, 75]

[52] E. Carlson, C. Prehofer, C. Bettstetter, H. Karl, A. Wolisz. A Distributed End-to-End Reservation Protocol for IEEE 802.11-Based Wireless Mesh Networks. *IEEE Journal on Selected Areas in Communications*, 24(11):2018–2027, Nov. 2006. DOI:10.1109/JSAC.2006.881633 [Cited on p. 7, 11, 34, 44, 49, 69, 73, 78, 83]

[53] S. Ould Cheikh, A. Gueroui. Multi-hop bandwidth reservation in WMN-based IEEE 802.11s (MBRWMN). In *International Conference on Communications and Information Technology (ICCIT'2012)*, pp. 211–215, June 2012. DOI:10.1109/ICCITechnol.2012.6285793 [Cited on p. 7, 34]

[54] F. Nawab, K. Jamshaid, B. Shihada, P. H. Ho. Fair packet scheduling in Wireless Mesh Networks. *Ad Hoc Networks*, 13(Part B):414–427, 2014. DOI:10.1016/j.adhoc.2013.09.002 [Cited on p. 7, 44, 49, 69, 73]

[55] M. El-Gendy, A. Bose, K. Shin. Evolution of the Internet QoS and support for soft real-time applications. *Proceedings of the IEEE*, 91(7):1086–1104, July 2003. DOI:10.1109/JPROC.2003.814615 [Cited on p. 8]

[56] Q. Shen, X. Fang, P. Li, Y. Fang. Admission Control Based on Available Bandwidth Estimation for Wireless Mesh Networks. *IEEE Transactions Vehicular Technology*, 58(5): 2519–2528, June 2009. DOI:10.1109/TVT.2008.2006680 [Cited on p. 8]

[57] C. Su, K. Xue, P. Hong, H. Lu. A Novel Bandwidth Estimation Scheme Used in Admission Control for Wireless Mesh Networks. In *IEEE Workshops of International Conference on Advanced Information Networking and Applications (WAINA'2011)*, pp. 164–169, Mar. 2011. DOI:10.1109/WAINA.2011.57 [Cited on p. 8]

[58] X. Yang, Z. Rosberg, Z. Cao, R. Liu. Admission Control for Wireless Mesh Networks Based on Active Neighbor Bandwidth Reservations. In *IEEE International Conference on Communications (ICC'2010)*, pp. 1–6, Cape Town, South Africa, May 2010. DOI:10.1109/ICC.2010.5502668 [Cited on p. 8, 33, 44, 49]

[59] P. Zhao, X. Yang, J. Wang, B. Liu, J. Wang. BOR/AC: Bandwidth-aware Opportunistic Routing with Admission Control in Wireless Mesh Networks. In *Proceedings of IEEE INFOCOM'2012*, pp. 2701–2705, Orlando, FL, USA, Mar. 2012. DOI:10.1109/INFCOM.2012.6195682 [Cited on p. 8, 34]

[60] K. Valarmathi, N. Malmurugan. Distributed Channel Assignment and Congestion Control Routing in Wireless Mesh Networks. In *3rd International Conference on Electronics Computer Technology (ICECT'2011)*, vol. 5, pp. 148–153, Apr. 2011. DOI:10.1109/ICECTECH.2011.5941975 [Cited on p. 8, 35]

[61] A. U. Chaudhry, R. H. M. Hafez. Channel Assignment Using Topology Control Based on Power Control in Wireless Mesh Networks. In *Wireless Mesh Networks - Efficient Link Scheduling, Channel Assignment and Network Planning Strategies*, ch. 3. InTech, Aug. 2012. DOI:10.5772/2612 [Cited on p. 8, 39]

[62] Network simulator 3 (ns-3) [Online]. Available at: http://www.nsnam.org [Accessed 11 December 2014]. [Cited on p. 11]

[63] C. M. D. Viegas, F. Vasques. Real-Time Communication in IEEE 802.11 Wireless Mesh Networks: A Prospective Study. In *Proceedings of the 6th Doctoral Symposium in Informatics Engineering (DSIE'2011)*, pp. 251–262, Porto, Portugal, Jan. 2011. [Cited on p. 11]

[64] C. M. D. Viegas, F. Vasques, P. Portugal. Real-Time Communication Support in IEEE 802.11-based Wireless Mesh Networks. In M. Khosrow-Pour (Ed.), *Encyclopedia of Information Science and Technology*, ch. 713, pp. 7247–7259. IGI Global, Hershey, PA, USA, 3rd ed., 2014. DOI:10.4018/978-1-4666-5888-2.ch713 [Cited on p. 11, 12]

[65] C. M. D. Viegas, F. Vasques, P. Portugal, R. Moraes. A multi-hop resource reservation scheme to support real-time communication in IEEE 802.11s wireless mesh networks. SUBMITTED FOR PUBLICATION IN *Ad Hoc Networks*, 2015. [Cited on p. 12]

[66] M. Bahr, J. Wang, X. Jia. Routing in Wireless Mesh Networks. In Y. Zhang, J. Luo, H. Hu (Eds.), *Wireless Mesh Networking: Architectures, Protocols and Standards*, pp. 133–134. Taylor & Francis, New York, USA, 2006. [Cited on p. 18, 46]

[67] J. Kim, I. Lee. 802.11 WLAN: history and new enabling MIMO techniques for next generation standards. *IEEE Communications Magazine*, 53(3):134–140, Mar. 2015. DOI:10.1109/MCOM.2015.7060495 [Cited on p. 20]

[68] M. Gast. *802.11n: A Survival Guide.* O'Reilly Media, 2012. [Cited on p. 20]

[69] M. Gast. *802.11ac: A Survival Guide.* O'Reilly Media, 2013. [Cited on p. 21]

[70] L. Verma, M. Fakharzadeh, S. Choi. WiFi on Steroids: 802.11ac and 802.11ad. *IEEE Wireless Communications*, 20(6):30–35, Dec. 2013. DOI:10.1109/MWC.2013.6704471 [Cited on p. 21]

[71] E. Au, M. Cheong, C. Ngo, C. Cordeiro, W. Zhuang. The future of Wi-Fi [Guest Editorial]. *IEEE Communications Magazine*, 52(11):20–21, Nov. 2014. DOI:10.1109/MCOM.2014.6957138 [Cited on p. 22]

[72] W. Sun, O. Lee, Y. Shin, S. Kim, C. Yang et al. Wi-Fi could be much more. *IEEE Communications Magazine*, 52(11):22–29, Nov. 2014. DOI:10.1109/MCOM.2014.6957139 [Cited on p. 22]

[73] Q. Ni. Performance analysis and enhancements for IEEE 802.11e wireless networks. *IEEE Network*, 19(4):21–27, July 2005. DOI:10.1109/MNET.2005.1470679 [Cited on p. 24, 48]

[74] S. Mangold, S. Choi, G. Hiertz, O. Klein, B. Walke. Analysis of IEEE 802.11e for QoS support in wireless LANs. *IEEE Wireless Communications*, 10(6):40–50, 2003. DOI:10.1109/MWC.2003.1265851 [Cited on p. 24]

[75] K. Kosek-Szott, M. Natkaniec, S. Szott, A. Krasilov, A. Lyakhov et al. What's new for QoS in IEEE 802.11? *IEEE Network*, 27(6):95–104, Nov. 2013. DOI:10.1109/MNET.2013.6678933 [Cited on p. 25]

[76] C. Hartmann, S. Meister. A Quality of Service (QoS) Resource Management Architecture for Wireless Mesh Networks. In *14th EUNICE open European Summer School*, Sept. 2008. [Cited on p. 31]

[77] A. Sgora, D. Vergados, P. Chatzimisios. IEEE 802.11s Wireless Mesh Networks: Challenges and Perspectives. In F. Granelli, et al. (Eds.), *Mobile Lightweight Wireless Systems*, vol. 13, pp. 263–271. Springer Berlin Heidelberg, Berlin, 2009. DOI:10.1007/978-3-642-03819-8_25 [Cited on p. 31, 44, 68]

[78] K. Farkas, B. Plattner. Supporting Real-Time Applications in Mobile Mesh Networks. In *Proceedings of the MeshNets Workshop*, Budapest, Hungary, July 2005. [Cited on p. 31, 32]

[79] M. Pinheiro, S. Sampaio, F. Vasques, P. Souto. A DHT-based approach for Path Selection and Message Forwarding in IEEE 802.11s industrial Wireless Mesh Networks. In *IEEE Conference on Emerging Technologies Factory Automation (ETFA'2009)*, pp. 1–10, Mallorca, Spain, Sept. 2009. DOI:10.1109/ETFA.2009.5347111 [Cited on p. 31]

[80] K. Nichols, S. Blake, F. Baker, D. Black. Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers [Online]. Request for Comments (RFC) 2474, Internet Engineering Task Force, Dec. 1998. Available at: http://www.rfc-editor.org/rfc/rfc2474.txt [Accessed 20 May 2014]. [Cited on p. 32]

[81] R. McTasney, D. Grunwald, D. Sicker. Low Latency in Wireless Mesh Networks. In S. Misra et al. (Eds.), *Guide to Wireless Mesh Networks*, Computer Communications and Networks, pp. 379–424. Springer London, 2009. DOI:10.1007/978-1-84800-909-7_15 [Cited on p. 32]

[82] J. Rezgui, A. Hafid, M. Gendreau. Distributed Admission Control in Wireless Mesh Networks: Models, Algorithms, and Evaluation. *IEEE Transactions on Vehicular Technology*, 59(3):1459–1473, Mar. 2010. DOI:10.1109/TVT.2009.2039360 [Cited on p. 33, 41]

[83] E. Toscano, L. Lo Bello. Bandwidth-Efficient Admission Control for EDF-based Wireless Industrial Communication. In *IEEE International Symposium on Industrial Electronics (ISIE'2011)*, pp. 1186–1193, Gdansk, Poland, June 2011. DOI:10.1109/ISIE.2011.5984212 [Cited on p. 34]

[84] J. Gallardo, D. Makrakis, H. Mouftah. MARE: An Efficient Reservation-Based MAC Protocol for IEEE 802.11s Mesh Networks. In *2nd International Conference on Advances in Mesh Networks (MESH'2009)*, pp. 97–102, June 2009. DOI:10.1109/MESH.2009.25 [Cited on p. 35, 74]

[85] R. Ali, A. Hafid, J. Rezgui. An Enhanced Reservation Based Medium Access Control for Voice over Wireless Mesh Networks. *IEEE Transactions on Wireless Communications*, 11 (10):3540–3549, Oct. 2012. DOI:10.1109/TWC.2012.072512.111738 [Cited on p. 35, 75, 98]

[86] J. Camp, E. Knightly. The IEEE 802.11s Extended Service Set Mesh Networking Standard. *IEEE Communications Magazine*, 46(8):120–126, Aug. 2008. DOI:10.1109/MCOM.2008.4597114 [Cited on p. 35]

[87] T. Chen, S. Xu. Algorithm for Congestion Control in Wireless Mesh Network. In *WASE International Conference on Information Engineering (ICIE'2010)*, vol. 1, pp. 276–279, Aug. 2010. DOI:10.1109/ICIE.2010.72 [Cited on p. 36]

[88] M. Choi, J. Oh, Y. Han. Congestion Control based on AMC Scheme for WLAN Mesh Networks. In *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'2007)*, pp. 1–5, Sept. 2007. DOI:10.1109/PIMRC.2007.4394403 [Cited on p. 36]

[89] S. Kim, S. J. Lee, S. Choi. The Impact of IEEE 802.11 MAC Strategies on Multi-Hop Wireless Mesh Networks. In *2nd IEEE Workshop on Wireless Mesh Networks (WiMesh'2006)*, pp. 38–47, Reston, VA, USA, Sept. 2006. DOI:10.1109/WIMESH.2006.288619 [Cited on p. 36]

[90] M. Lacage, M. Manshaei, T. Turletti. IEEE 802.11 Rate Adaptation: a Practical Approach. In *Proceedings of the 7th ACM international symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'2004)*, pp. 126–134, New York, NY, USA, 2004. DOI:10.1145/1023663.1023687 [Cited on p. 36, 37]

[91] W. Kim, O. Khan, K. T. Truong, S. H. Choi, R. Grant et al. An Experimental Evaluation of Rate Adaptation for Multi-Antenna Systems. In *Proceedings of IEEE INFOCOM'2009*, pp. 2313–2321, Rio de Janeiro, Brazil, Apr. 2009. DOI:10.1109/INFCOM.2009.5062157 [Cited on p. 36]

[92] S. Vitturi, L. Seno, F. Tramarin, M. Bertocco. On the Rate Adaptation Techniques of IEEE 802.11 Networks for Industrial Applications. *IEEE Transactions on Industrial Informatics*, 9(1):198–208, Feb. 2013. DOI:10.1109/TII.2012.2189223 [Cited on p. 37]

[93] J. Y. Lee, T. Shen, K. G. Shin, Y. J. Suh, C. Yu. Multihop Transmission Opportunity in Wireless Multihop Networks. In *Proceedings of IEEE INFOCOM'2010*, pp. 1–9, San Diego, CA, USA, Mar. 2010. DOI:10.1109/INFCOM.2010.5462112 [Cited on p. 38]

[94] H. Mogaibel, M. Othman, S. Subramaniam, N. Hamid. Channel Reservation Scheme Based on AODV Routing Protocol for Common Traffic in Wireless Mesh Network. In *Proceedings of the Second International Conference on Computer and Network*

Technology (ICCNT'2010), pp. 168–174, Bangkok, Thailand, 2010. IEEE Computer Society. DOI:10.1109/ICCNT.2010.43 [Cited on p. 38, 41]

[95] P. Kyasanur, J. So, C. Chereddi, N. H. Vaidya. Multi-Channel Mesh Networks: Challenges and Protocols. *IEEE Wireless Communications*, 13(2):30–36, Apr. 2006. DOI:10.1109/MWC.2006.1632478 [Cited on p. 39]

[96] J. Hoblos, H. Peyravi. Fair access rate (FAR) provisioning in multi-hop multi-channel wireless mesh networks. In *International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT'2010)*, pp. 68–73, Oct. 2010. DOI:10.1109/ICUMT.2010.5676656 [Cited on p. 39]

[97] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini, M. Conti. Channel Assignment Strategies for Multiradio Wireless Mesh Networks: Issues and Solutions. *IEEE Communications Magazine*, 45(11):86–95, Nov. 2007. DOI:10.1109/MCOM.2007.4378326 [Cited on p. 39, 40]

[98] A. Raniwala, K. Gopalan, T. Chiueh. Centralized Channel Assignment and Routing Algorithms for Multi-Channel Wireless Mesh Networks. *SIGMOBILE Mobile Computing and Communications Review*, 8(2):50–65, Apr. 2004. DOI:10.1145/997122.997130 [Cited on p. 39]

[99] S. Ghannay, S. M. Gammar. Joint routing and channel assignment protocol for multi-radio multi-channel IEEE 802.11s mesh networks. In *4th Joint IFIP Wireless and Mobile Networking Conference (WMNC'2011)*, pp. 1–8, Oct. 2011. DOI:10.1109/WMNC.2011.6097251 [Cited on p. 39]

[100] L. Bononi, M. Di Felice, A. Molinaro, S. Pizzi. Enhancing multi-hop communication over multi-radio multi-channel wireless mesh networks: A cross-layer approach. *Elsevier Computer Communications*, 34(13):1559–1569, Aug. 2011. DOI:10.1016/j.comcom.2010.12.002 [Cited on p. 40]

[101] M. Fathi, H. Taheri, M. Mehrjoo. Cross-Layer Joint Rate Control and Scheduling for OFDMA Wireless Mesh Networks. *IEEE Transactions on Vehicular Technology*, 59(8): 3933–3941, Oct. 2010. DOI:10.1109/TVT.2010.2064346 [Cited on p. 41]

[102] K. Mase. Layer 3 Wireless Mesh Networks: Mobility Management Issues. *IEEE Communications Magazine*, 49(7):156–163, July 2011. DOI:10.1109/MCOM.2011.5936169 [Cited on p. 44, 68]

[103] A. Hamidian, U. Körner. Distributed Reservation-based QoS in Ad Hoc Networks with Internet Access Connectivity. In *21st IEEE International Teletraffic Congress*, pp. 1–8, Paris, France, Sept. 2009. [Cited on p. 44, 49]

[104] R. Moraes, F. Vasques, P. Portugal. A 2-tier Architecture to Support Real-Time Communication in CSMA-Based Networks. In *IEEE Network Operations and Management Symposium (NOMS'2008)*, pp. 1061–1066, Salvador, Bahia, Brazil, Apr. 2008. DOI:10.1109/NOMS.2008.4575279 [Cited on p. 44]

[105] M. Pinheiro, F. Vasques, S. Sampaio, P. Souto. DHT-based Cluster Routing Protocol for IEEE802.11s Mesh networks. In *6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops (SECON Workshops'2009)*, pp. 1–6, Rome, Italy, June 2009. DOI:10.1109/SAHCNW.2009.5172928 [Cited on p. 44]

[106] A. Lyakhov, I. Pustogarov. Intra-flow Interference Study in IEEE 802.11s Mesh Networks. In B. B. et al. (Ed.), *Multiple Access Communications*, vol. 7642 of *Lecture Notes in Computer Science*, pp. 127–138. Springer Berlin Heidelberg, Berlin, 2010. DOI:10.1007/978-3-642-15428-7_14 [Cited on p. 45, 69]

[107] R. Moraes, P. Portugal, F. Vasques, R. Custódio. Assessment of the IEEE 802.11e EDCA protocol limitations when dealing with real-time communication. *EURASIP Journal on Wireless Communications and Networking*, 2010:1–14, Apr. 2010. DOI:10.1155/2010/351480 [Cited on p. 45, 46, 48, 61, 62, 69]

[108] R. Moraes, P. Portugal, F. Vasques. Simulation Analysis of the IEEE 802.11e EDCA Protocol for an Industrially-Relevant Real-Time Communication Scenario. In *IEEE Conference on Emerging Technologies and Factory Automation (ETFA'2006)*, pp. 202–209, Prague, Czech Republic, Sept. 2006. DOI:10.1109/ETFA.2006.355207 [Cited on p. 45]

[109] C. E. Perkins, E. Belding-Royer, S. Das. Ad hoc On-Demand Distance Vector (AODV) Routing [Online]. Request for Comments (RFC) 3561, Internet Engineering Task Force, July 2003. Available at: http://www.rfc-editor.org/rfc/rfc3561.txt [Accessed 20 May 2014]. [Cited on p. 46]

[110] D.-J. Deng, R.-s. Chang. A Priority Scheme for IEEE 802.11 DCF Access Method. *IEICE Transactions Communication (Japan)*, E82-B(1):96–102, Jan. 1999. [Cited on p. 48]

[111] G.-H. Hwang, D.-H. Cho. Performance Analysis on Coexistence of EDCA and Legacy DCF Stations in IEEE 802.11 Wireless LANs. *IEEE Transactions on Wireless Communications*, 5(12):3355–3359, Dec. 2006. DOI:10.1109/TWC.2006.256955 [Cited on p. 48]

[112] C. Calafate, P. Manzoni, M. Malumbres. Assessing the effectiveness of IEEE 802.11e in multi-hop mobile network environments. In *Proceedings of 12th Annual International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunications Systems (MASCOTS'2004)*, pp. 205–212, Oct. 2004. DOI:10.1109/MASCOT.2004.1348232 [Cited on p. 48]

[113] B. Xiang, M. Yu-Ming. The Impact of Hidden Nodes on MAC Layer Performance of Multi-Hop Wireless Networks Using IEEE802.11e Protocol. In *International Conference on Wireless Communications, Networking and Mobile Computing (WiCom'2007)*, pp. 1479–1483, Sept. 2007. DOI:10.1109/WICOM.2007.374 [Cited on p. 48]

[114] K. Xu, M. Gerla, S. Bae. Effectiveness of RTS/CTS handshake in IEEE 802.11 based ad hoc networks. *Ad Hoc Networks*, 1(1):107–123, 2003. DOI:10.1016/S1570-8705(03)00015-5 [Cited on p. 48]

[115] J. Bicket, D. Aguayo, S. Biswas, R. Morris. Architecture and Evaluation of an Unplanned 802.11B Mesh Network. In *Proceedings of the 11th Annual International Conference on Mobile Computing and Networking (MobiCom'2005)*, pp. 31–42, Cologne, Germany, 2005. DOI:10.1145/1080829.1080833 [Cited on p. 48]

[116] G. Anastasi, M. Conti, E. Gregori. IEEE 802.11 in Ad Hoc Networks: Protocols, Performance and Open Issues. In S. Basagni et al. (Eds.), *Mobile Ad Hoc Networking*, pp. 69–116. IEEE Press – John Wiley & Sons, New Jersey, USA, 2004. [Cited on p. 49]

[117] R. Braden, L. Zhang, S. Berson. Resource ReSerVation Protocol (RSVP) – Version 1 Functional Specification [Online]. Request for Comments (RFC) 2205, Internet Engineering Task Force, Sept. 1997. Available at: http://www.rfc-editor.org/rfc/rfc2205.txt [Accessed 26 May 2014]. [Cited on p. 50]

[118] R. Fielding, J. Gettys, J. C. Mogul, H. Frystyk, L. Masinter et al. Hypertext Transfer Protocol – HTTP/1.1 [Online]. Request for Comments (RFC) 2616, Internet Engineering Task Force, June 1999. Available at: http://www.rfc-editor.org/rfc/rfc2616.txt [Accessed 28 May 2014]. [Cited on p. 51]

[119] B. A. Mah. An empirical model of HTTP network traffic. In *Proceedings of 16th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'1997)*, vol. 2, pp. 592–600, Kobe, Japan, 1997. DOI:10.1109/INFCOM.1997.644510 [Cited on p. 51]

[120] C. Park, H. Shen, J. Marron, F. Hernandez-Campos, D. Veitch. Capturing the Elusive Poissonity in Web Traffic. In *14th IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS'2006)*, pp. 189–196, Monterey, CA, USA, 2006. DOI:10.1109/MASCOTS.2006.17 [Cited on p. 51]

[121] I. Aktas, T. King, C. Mengi. Modeling Application Traffic. In K. Wehrle, M. Güneş, J. Gross (Eds.), *Modeling and Tools for Network Simulation*, pp. 397–426. Springer Berlin Heidelberg, Berlin, 2010. DOI:10.1007/978-3-642-12331-3_18 [Cited on p. 51]

[122] L. E. Miller. Validation of 802.11a/UWB Coexistence Simulation [Online]. Tech. rep., National Institute of Standards and Technology, Gaithersburg, MD, USA, Oct. 2003. Available at: http://www.antd.nist.gov/wctg/manet/docs/coexvalid_031017.pdf [Accessed 10 March 2014]. [Cited on p. 54]

[123] G. Pei, T. R. Henderson. Validation of OFDM error rate model in ns-3 [Online]. Tech. rep., Boeing Research & Technology, Seattle, WA, USA, 2010. Available at: http://www.nsnam.org/~pei/80211ofdm.pdf [Accessed 10 March 2014]. [Cited on p. 54, 85]

[124] G. Lukas, T. Lindhorst, E. Nett. Modeling Medium Utilization for Admission Control in Industrial Wireless Mesh Networks. In *30th IEEE Symposium on Reliable Distributed Systems (SRDS'2011)*, pp. 65–74, Madrid, Spain, Oct. 2011. DOI:10.1109/SRDS.2011.17 [Cited on p. 55]

[125] A. Torres, C. T. Calafate, J.-C. Cano, P. Manzoni. Assessing the IEEE 802.11e QoS effectiveness in multi-hop indoor scenarios. *Ad Hoc Networks*, 10(2):186–198, 2012. DOI:10.1016/j.adhoc.2010.07.011 [Cited on p. 68]

[126] H. Zhao, E. Garcia-Palacios, S. Wang, J. Wei, D. Ma. Evaluating the impact of network density, hidden nodes and capture effect for throughput guarantee in multi-hop wireless networks. *Ad Hoc Networks*, 11(1):54–69, 2013. DOI:10.1016/j.adhoc.2012.04.007 [Cited on p. 68]

[127] K. Kosek-Szott. A survey of MAC layer solutions to the hidden node problem in ad-hoc networks. *Ad Hoc Networks*, 10(3):635–660, 2012. DOI:10.1016/j.adhoc.2011.10.003 [Cited on p. 68]

[128] M. Zogkou, A. Sgora, P. Chatzimisios, D. Vergados. EDCA mechanism and mobility support evaluation in IEEE 802.11s WMNs. In *6th International Congress on Ultra*

Modern Telecommunications and Control Systems and Workshops (ICUMT'2014), pp. 204–209, Oct. 2014. DOI:10.1109/ICUMT.2014.7002103 [Cited on p. 68]

[129] A. Hamidian, U. Körner. Extending EDCA with distributed resource reservation for QoS guarantees. *Telecommunication Systems*, 39(3–4):187–194, Dec. 2008. DOI:10.1007/s11235-008-9124-y [Cited on p. 69, 73]

[130] E. Khorov, A. Krasilov, A. Lyakhov, D. Ostrovsky. Dynamic Resource Allocation for MCCA-Based Streaming in Wi-Fi Mesh Networks. In G. Bianchi, A. Lyakhov, E. Khorov (Eds.), *Wireless Access Flexibility*, vol. 8072 of *Lecture Notes in Computer Science*, pp. 93–111. Springer Berlin Heidelberg, 2013. DOI:10.1007/978-3-642-39805-6_9 [Cited on p. 69, 75, 76]

[131] Y. Javed, A. Baig, M. Maqbool. Enhanced quality of service support for triple play services in IEEE 802.11 WLANs. *EURASIP Journal on Wireless Communications and Networking*, 2015(1):9, 2015. DOI:10.1186/s13638-014-0233-x [Cited on p. 74]

[132] S. Chakraborty, S. Nandi. IEEE 802.11s Mesh Backbone for Vehicular Communication: Fairness and Throughput. *IEEE Transactions on Vehicular Technology*, 62(5):2193–2203, June 2013. DOI:10.1109/TVT.2013.2239672 [Cited on p. 75]